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IN MEMORIAM: JÓZSEF KERTÉSZ

József Kertész, former district engineer of Szigetköz at the North Transdanubian Water Directorate, generously shared his deep local knowledge and many stories from the periods covered in this book. His insights helped shape the story presented here, and he also provided many of the photographs used throughout the book. Sadly, he passed away while the book was being finalized and could not see it through to completion.

We will remember his contribution to the understanding and preservation of Szigetköz with gratitude.

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Executive Summary

Szigetköz, located in northwestern Hungary, is an inland delta of the Danube River and supports a diverse and dynamic floodplain ecosystem. Over the centuries, the Danube naturally fragmented across this terrain into multiple braided river branches, creating one of Central Europe's most complex and valuable floodplains. This extensive network of channels, oxbows, and wetlands has provided critical habitats for various aquatic and terrestrial species. Today, the Danube marks the border between Hungary and Slovakia, and the southernmost branch—known as the Mosoni-Danube—defines the lower boundary of this river network. Szigetköz lies between these two river systems, covering approximately 375 km². A similarly structured floodplain, Csallóköz (Žitný Ostrov), lies on the Slovak side.

Historically, human settlements in the region have coexisted with the Danube's natural changes. From the nineteenth century onward, large-scale river engineering and water-management projects significantly reshaped the region. Following regulation of the upper Danube, Hungary and Czechoslovakia sought to improve navigation conditions, generate hydropower, and enhance flood safety. After decades of planning, the two countries signed a treaty in 1977 to implement the Gabčíkovo–Nagymaros Barrage Project. The project envisaged three principal hydraulic structures: (1) a barrage at Dunakiliti, (2) the Gabčíkovo Hydropower Plant, and (3) a downstream barrage at Nagymaros. Hungary later suspended construction on its territory amid political and environmental concerns, while Czechoslovakia proceeded with an alternative arrangement known as Variant C. In 1992, Czechoslovakia unilaterally diverted approximately 80% of the Danube's flow into the power canal, bypassing the natural riverbed. The diversion resulted in severe ecological degradation in Szigetköz, including lower water levels, the drying of floodplain habitats, and major disruption of the region's hydrological regime. Water replenishment of the Szigetköz branch system had formed part of the original project concept but remained incomplete. It therefore had to be reassessed and redesigned for the new hydrological conditions.

The North-Transdanubian Water Directorate coordinated the planning, implementation, and long-term operation of a staged damage-mitigation and floodplain-rehabilitation program. Between 1992 and 2022, the program partially re-established water levels and flow dynamics in the Szigetköz branch systems by combining controlled water allocation, gravity-driven conveyance, adjustable water-control structures, fish-passage measures, monitoring, and adaptive operation. Rather than recreating an undisturbed natural floodplain, the program improved selected hydrological, ecological, and water-use functions within a heavily modified, internationally regulated river system.

The rehabilitation project involved solving complex hydrological and technical problems, working within international agreements, and fostering cooperation among diverse stakeholders.

One of the most significant challenges was building mutual trust and reaching agreement on rehabilitation objectives among local communities, government institutions, water management authorities, scientists, and environmental organizations. These negotiations were essential for reconciling ecological objectives with social and economic interests and for establishing a durable basis for the long-term operation and further development of the system. Within these constraints, the Szigetköz rehabilitation constitutes a success story in large-scale floodplain rehabilitation. Its success lies not only in the implemented hydraulic measures and their long-term operation, but also in the establishment of monitoring, adaptive management, stakeholder co-operation, and institutional mechanisms capable of responding to changing ecological and water-use requirements.

Prepared within DALIA Demonstration Pilot Site 1, this publication presents the Szigetköz rehabilitation as both a success story and a transferable case study, rather than as a universally applicable technical blueprint. It combines the historical reconstruction of the interventions with an assessment of the planning, technical, ecological, institutional, and operational decisions that shaped the present system. The case study examines eight practices that may inform other large-scale floodplain rehabilitation projects:

- (1) selecting a historically and hydrologically defensible reference period instead of assuming an idealized pristine condition;*
- (2) translating ecological requirements into measurable hydraulic and operational targets;*
- (3) favoring gravity-based and low-maintenance operation, using adjustable structures, and considering removability where technically feasible and locally appropriate;*
- (4) using test operation and monitoring results to refine permanent operating rules;*
- (5) converting competing stakeholder needs into explicit functions, priorities, and operating rules;*
- (6) maintaining a permanent multi-stakeholder forum for annual review, conflict resolution, and adaptive management;*
- (7) planning rehabilitation at the scale of the whole river corridor, even where implementation must be divided into phases; and*
- (8) extending existing systems by retaining and redistributing available water while restoring hydraulic and ecological connections.*

These practices should not be transferred mechanically. Their applicability to another river system depends on local hydrology, sediment dynamics, ecological objectives, available water resources, legal and transboundary arrangements, institutional capacity, stakeholder relationships, and monitoring resources. Accordingly, the following chapters distinguish between site-specific solutions and broadly applicable principles. For each major project phase, they identify the problem addressed, the decision-making method applied, the evidence available, the limitations encountered, and the conditions required for application elsewhere.

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1. GENERAL OVERVIEW

This chapter defines the physical and socio-ecological system within which the Szigetköz rehabilitation was designed and is operated. It describes the region's spatial units, alluvial geology and aquifer system, soils, hydrological regime, surface water–groundwater interactions, water quality, climate, land use, habitats, protected areas, ecosystem services, settlements, and water-dependent economic activities. These conditions determine both the ecological objectives and the technical, legal, and social constraints of rehabilitation. To support knowledge transfer, the chapter distinguishes characteristics specific to Szigetköz from diagnostic questions that are relevant to other large floodplains.



Figure 1: Danube River at Dunaremete



Transferable lesson 1 — Define the system before selecting measures

Challenge addressed

Floodplain degradation is rarely caused by a single pressure. River discharge, surface connectivity, groundwater, sediment transport, water quality, flood protection, land use, habitats, and water demands interact across administrative and national boundaries.

Approach used in Szigetköz

The rehabilitation area was treated as a system of hydrologically distinct but interacting units: the Old Danube, the active floodplain branch system, the historical floodplain channel network, the Mosoni-Danube, and the underlying groundwater system. These units were considered together with protected habitats, settlements, land uses, economic activities, and institutional responsibilities.

General principle

Define the hydrological, ecological, socio-economic, and institutional boundaries of the rehabilitation system before selecting individual measures.

Evidence and operational relevance

The later monitoring system connected information needs, monitoring strategy, sampling, analysis, reporting, and the use of results in system operation. It included hydromorphological, physicochemical, and biological components rather than relying on water level alone.

Conditions for transfer

Application elsewhere requires a shared spatial baseline, information on surface water–groundwater interactions, identification of protected and water-dependent assets, and cooperation among the institutions responsible for water, nature conservation, land use, and flood protection.

Suggested indicators

Surface-water connectivity; groundwater level and depth; discharge and water-level variability; water residence time; sediment processes; water quality; habitat diversity; biological quality elements; ecosystem services; and exposure of settlements and land uses.

General overview

The Danube is Europe's second-longest river and forms the central section of the approximately 3,500 km Rhine–Main–Danube inland waterway, which connects the North Sea and the Black Sea. The river and its extensive catchment support navigation, water supply, energy production, agriculture, recreation, and a wide range of ecosystem services. However, the physical character and functions of the river vary considerably along its course. Downstream of Bratislava, the Danube leaves the confined Alpine–Carpathian corridor and enters the lower-gradient Little Hungarian Plain, where its channel becomes broader, and its capacity to transport coarse sediment decreases. The present-day Old Danube at *Dunaremete* is shown in Figure 1. The location of Szigetköz within the European waterway system is shown in Figure 2.

In the Szigetköz area, sediment deposition and channel migration created numerous islands within an intricate river branch system. This wider multi-channel floodplain landscape is commonly referred to as an inland delta (Jakus et al., 2024), while Szigetköz itself is a large river island within this system. Hungarian river regulation in the nineteenth century reshaped and progressively stabilized the main channel, now generally known as the Old Danube. Today, the Old Danube marks the border between Hungary and Slovakia along most of the Szigetköz reach.

The Mosoni-Danube forms the southernmost major branch of the Danube in this network. The area enclosed by the Old Danube and the Mosoni-Danube is known as Szigetköz in Hungarian, Kleine Schüttinsel in German, and Malý Žitný ostrov in Slovak. With a land area of approximately 375 km², Szigetköz is generally described as Hungary's largest river island. A substantially larger, hydrologically related island lies on the Slovak side, known as Csallóköz in Hungarian, Große Schüttinsel in German, and Žitný ostrov in Slovak. Although Csallóköz is not the primary focus of this study, the two areas form parts of the same transboundary alluvial and hydrological system. An overview of the principal geographical and hydraulic features of Szigetköz is presented in Figure 3.

Human communities have adapted over the centuries to this dynamic environment, which the river continuously reshapes. At the same time, successive water-management interventions profoundly influenced the region's development and current structure. Economic growth, the expansion of steam navigation, and increasing transport demands during the nineteenth century encouraged large-scale river-regulation works in Hungary. These measures aimed primarily to improve navigation by concentrating the flow of the complex, multi-channel Danube system into a principal channel, the Old Danube.



Figure 2: Location of Szigetköz along the Rhine–Main–Danube waterway

By the early twentieth century, flood-protection levees had been constructed on both sides of the river, formally dividing the former floodplain into active and historical floodplain compartments. The active floodplain, situated between the levees, is intersected by several river branches. The islands between them are covered mainly by natural floodplain forests and poplar plantations. The historical floodplain, situated behind the flood-protection levees, is a composite landscape characterized by diverse land uses. Most of this area is used for agriculture, particularly arable farming, while smaller areas of meadows, pastures, forest strips, canals, oxbow lakes, marshes, reedbeds, and other wetlands contribute to the landscape's ecological diversity.

The Szigetköz region has undergone substantial transformation as a result of large-scale water-management projects, including river regulation, the construction of flood-protection levees, and the development of the Gabčíkovo Hydropower Plant. The diversion of a large proportion of the Danube's discharge altered water levels, discharge distribution, groundwater conditions, sediment processes, and ecological connectivity, creating the need for water-replenishment systems in both the active and historical floodplains. River regulation, levee construction, channel closures, and the later diversion of the Danube progressively fragmented the formerly more interconnected river branch network. The water-replenishment systems were developed to mitigate these hydrological and ecological impacts by improving water availability and selected connections within the modified system. They should therefore be understood as rehabilitation and damage-mitigation measures rather than as causes of fragmentation or as a complete recreation of an undisturbed floodplain. Figure 4 illustrates the present spatial separation of the main water bodies and floodplain compartments in the Szigetköz–Csallóköz area.

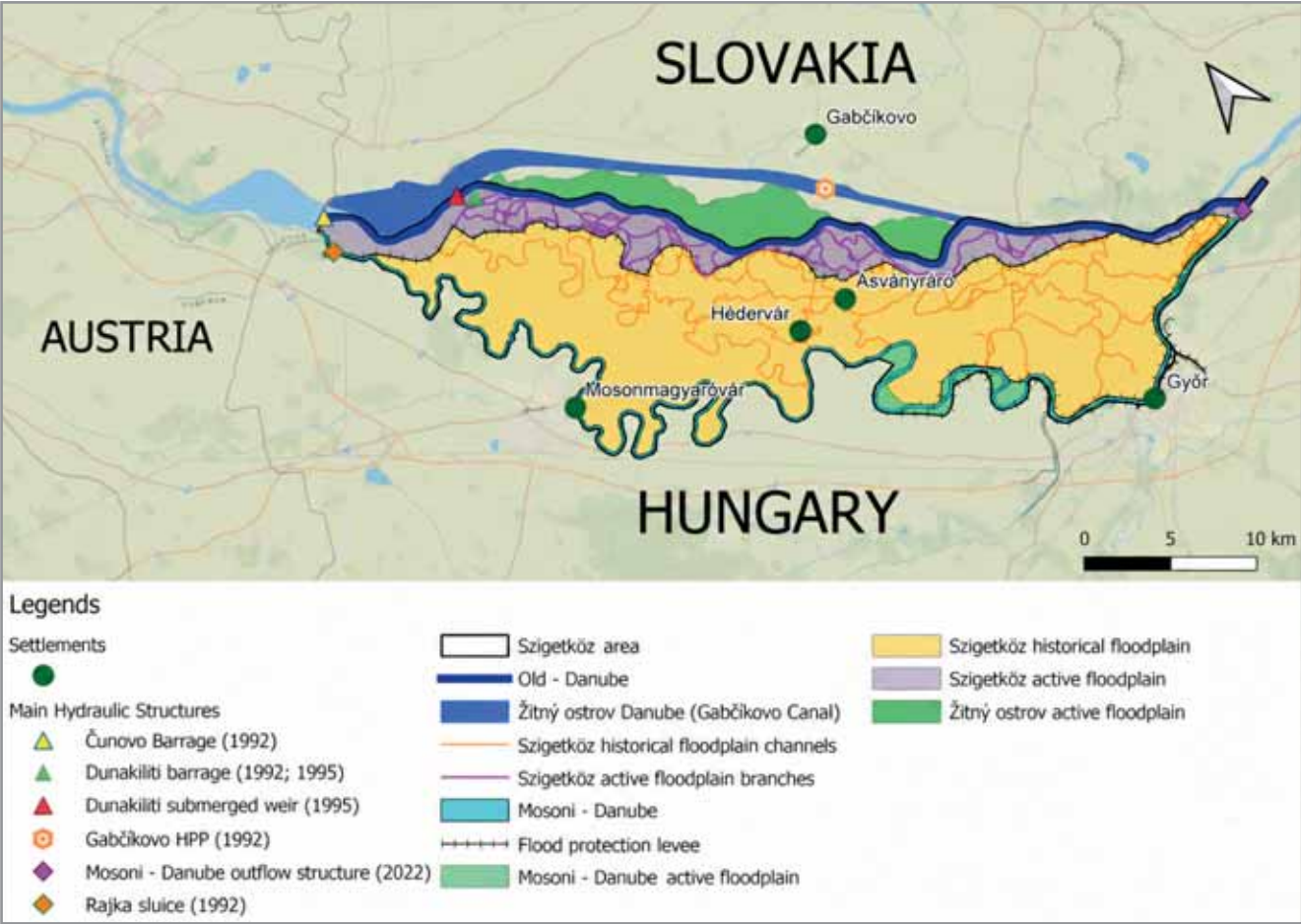


Figure 3: An Overview Map of the Szigetköz Area. The ESRI basemap was supplemented with project geospatial data processed in QGIS

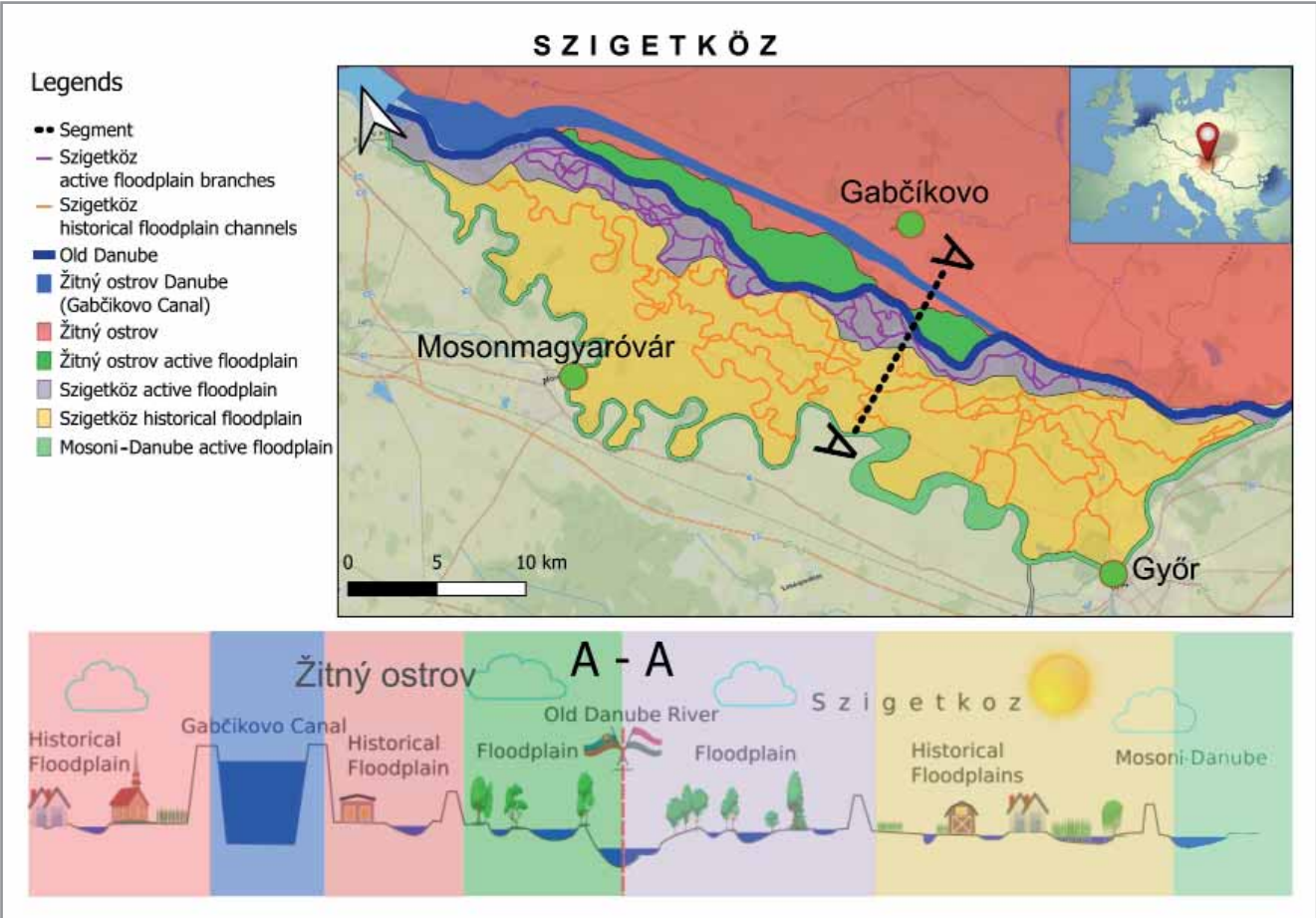


Figure 4: Spatially Separated Water Bodies in The Szigetköz-Csallóköz (Žitný Ostrov) Area

This development history also explains why several water bodies in the region are classified as heavily modified. Under the EU Water Framework Directive, the relevant environmental objective for such water bodies is the achievement of good ecological potential, supported by feasible hydromorphological and ecological mitigation measures, rather than the complete restoration of an assumed pristine condition (European Parliament and Council, 2000; Pannonhalmi, 2005). For this reason, the following overview does not treat geology, hydrology, ecology, and society as unrelated background topics. It shows how these factors jointly defined the rehabilitation objectives, design constraints, monitoring requirements, stakeholder interests, and operating rules discussed in the subsequent chapters.

1.1. Szigetköz today: spatial and socio-economic context

The broader Szigetköz region comprises 29 settlements. Győr and Mosonmagyaróvár serve as the region's main regional centers and together account for more than 80% of the region's population. In recent decades, several smaller settlements have experienced population growth, partly due to commuters relocating from the larger cities, although the overall population density remains below the national average. The line between Hédervár and Ásványráró conventionally divides the settlements into Upper and Lower Szigetköz.

The region's natural resources continue to influence its economic structure. Thermal water supports health and wellness tourism in settlements such as Lipót and Mosonmagyaróvár, while open-pit sand and gravel extraction supplies materials to the construction sector (Insula Magna Project, 2022). These activities coexist with ecological rehabilitation and nature-conservation objectives, illustrating the region's simultaneous dependence on natural resources for economic production, recreation, and environmental quality. Historically, local communities relied heavily on the Danube and its tributaries for fishing, hunting, forestry, and other water-related livelihoods.



River regulation and the construction of flood-protection levees reduced access to traditional river-based livelihoods and contributed to a gradual shift towards agriculture, supported by the fertile alluvial soils and favorable climatic conditions of Szigetköz. Although agriculture remains important, livestock farming and the number of primary producers have declined since the economic and ownership changes of the 1990s. At the same time, demand for locally sourced, high-quality food has increased, particularly in the nearby urban markets. Products such as honey, cheese, jams, and processed vegetables have become more prominent and are increasingly marketed through local and community-supported agricultural initiatives. Ecotourism has also developed over the last two decades, particularly in areas where the rehabilitation of side channels and wetlands has increased the floodplain's recreational and landscape value. Fishing, canoeing, kayaking, birdwatching, and cycling, including routes connected to the EuroVelo network, have become important attractions. Nevertheless, tourism infrastructure remains underdeveloped (Kézai et al., 2022). Many smaller settlements have limited accommodation, catering, and related visitor services, restricting year-round tourism and concentrating demand in the main season. Examples of land use and water-related recreation are shown in Figure 5.

Forestry and hunting previously played a more prominent role in the regional economy but have declined because of environmental changes and reduced profitability. Hunting associations nevertheless remain active in local communities, particularly through environmental education programs for schools. These activities may provide a basis for the further development of regional forest school and environmental awareness initiatives (ÉDUVIZIG, 2020).

Since the 1990s, the industrial structure of Szigetköz has changed substantially. The decline of several large industrial plants was followed by a concentration of economic activity around Győr and Mosonmagyaróvár. Machinery and automotive production dominate the industrial economy of Győr, which also has an important food-processing sector, while Dunakiliti is likewise characterized by food



Figure 5: Examples of land use and water-related recreation in Szigetköz

production. Manufacturing remains a major source of employment and is strongly influenced by foreign-owned companies. Small and micro-enterprises generally operate in local trades and services, including carpentry, masonry, retail, and related activities. Their development is often constrained by limited capital resources and relatively low employment capacity.

Figure 6 illustrates the structure of the active workforce in Szigetköz. Entrepreneurs account for 28% of the total workforce, primary producers for 14%, and nonprofit organizations for 4%. The remaining 54% is presented through a sectoral breakdown: services account for 44% of the total workforce, manufacturing and construction for 8%, and agriculture for 2%. The figure therefore indicates that services form the largest employment category, while manufacturing, construction, and agriculture represent substantially smaller shares. It also reflects the long-term transition from traditional primary-sector livelihoods towards services, entrepreneurship, and industrial employment. According to the Insula Magna Project (2022), the economy of Szigetköz is relatively advanced and dynamic compared with the Hungarian national and West Transdanubian averages. Development is nevertheless uneven among settlements and reflects differences in access to urban centers, infrastructure, investment, and cross-border economic connections. Foreign capital plays a particularly important role in the more developed micro-regions, where companies primarily supply the automotive, electronics, food processing, and light industries. At the same time, the region faces labor shortages because demand from nearby Austria attracts skilled workers, including car-

penters, welders, industrial mechanics, and toolmakers. Cross-border employment therefore provides economic opportunities for residents but may also limit the availability of skilled labor for local enterprises.

The socio-economic structure of Szigetköz is directly relevant to floodplain rehabilitation. Agriculture, tourism, forestry, fisheries, settlements, industrial activities, and nature conservation depend on the same interconnected surface-water and groundwater system, but their water-related requirements are not always identical. Understanding these dependencies is therefore necessary to identify stakeholders, evaluate trade-offs, and develop operating rules that balance ecological objectives with regional social and economic needs.

1.2. Geological setting

Szigetköz lies within the Pannonian Basin. The Carpathians, Eastern Alps, and Dinarides, which surround the Basin, resulted from Mesozoic and Cenozoic (250-50 Ma) continental collision between Europe and several continental fragments to the south, including Africa. Studies using subsurface data have shown that the Pannonian area was extensively deformed by Mesozoic thrusting and subsequently disrupted by a Mediterranean back-arc extensional basin—a basin formed as the crust stretched behind a mountain-building zone—of Middle Miocene age. The Basin is actually a system of small, deep basins separated by relatively shallow basement blocks. The Neogene-Quaternary (20-0 Ma) sedimentary rocks exceed 7 km in thickness in some areas, and the basin system

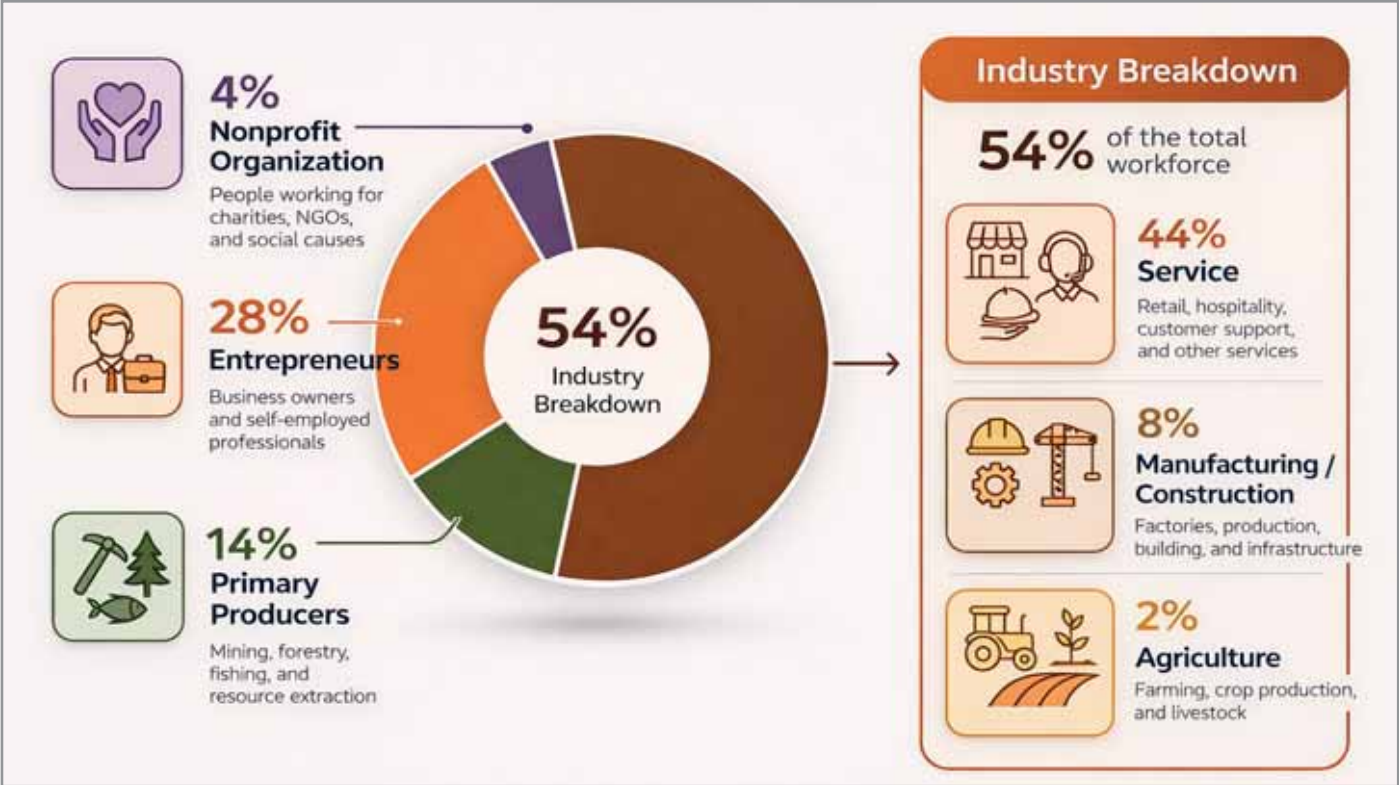


Figure 6: Workforce distribution (Total workforce=100%) (Insula Magna Project, 2022)

(including the Transylvanian basin) is about 400 km from north to south and 800 km from east to west. Most researchers currently interpret it as a Mediterranean back-arc extensional basin of middle Miocene age (20–7 Ma), as shown in Figure 7. The deep basins received large volumes of sediments transported from the progressively upthrusting Alps, Carpathians, and Dinarides. Figure 8a shows the general location of the Hungarian Little Plain (in Hungarian: Kisalföld) (HLP), while Figure 8b shows a more detailed location. The sedimentary fill of the HLP, like any other part of the Pannonian Basin System, includes Early to Middle Miocene marine sediments of the Paratethys (a large inland sea that once covered parts of Central and Eastern Europe), Middle Miocene restricted marine deposits, and brackish to freshwater deposits of Lake Pannon and the adjacent fluvial systems (Pannonian, i.e., Late Miocene – Pliocene, 10 – 5 Ma), Sztanó et al. (2016).

Adding to the geologic evolution, volcanism occurred throughout the Miocene. That early activity has led to numerous locations of geothermal hot spots, thermal bath sources, and potential thermal reservoirs for energy exploitation. Additionally, the Basin region has significant hydrocarbon reserves, including petroleum and natural gas. Exploration and mapping have continued for decades to the present.

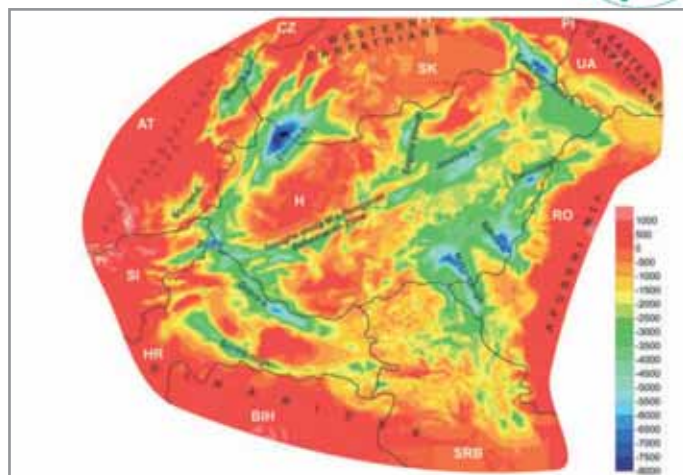


Figure 7: Depths of the Pannonian Basin, showing the deepest basin in the Danube-HLP region (Rman et al., 2021)

The Ancient Danube's sediment deposition during the Quaternary period resulted in an alluvial cone composed of gravel and sandy gravel. The thickness of these river deposits varies considerably, ranging from about 20 meters near Bratislava to 220 meters near Mosonmagyaróvár and up to 300 meters in the Middle Szigetköz region, then gradually decreasing towards East in the Lower Szigetköz area (Figure 9).

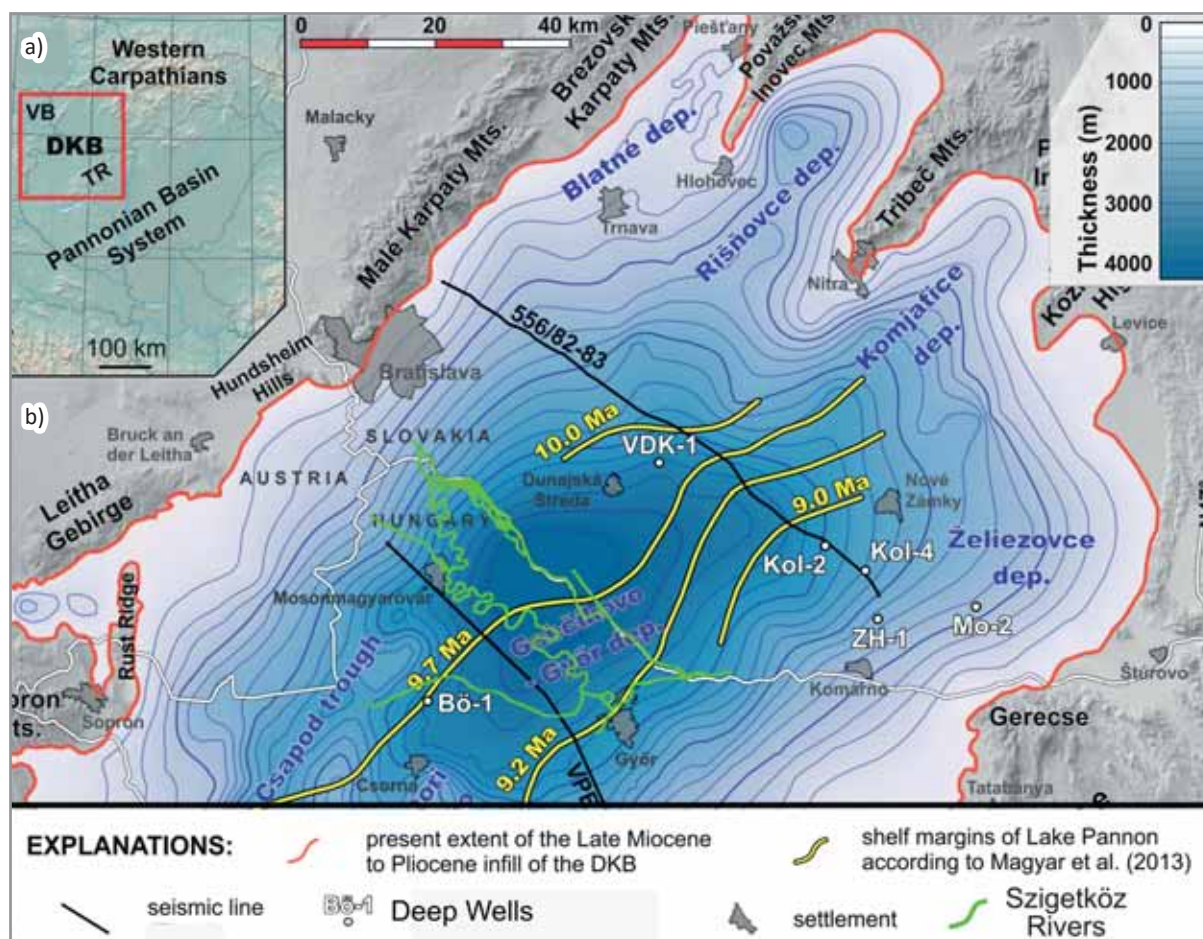


Figure 8: a) Location of the Hungarian Little Plain in the Eastern Alps–Western Carpathians–Pannonian Basin junction area (TR: Transdanubian Range, VB: Vienna Basin). b) Map of the HLP with thickness of the Late Miocene to Quaternary succession (Sztanó et al., 2016). Thickness data modified from Atzenhofer et al. (2011). The reconstructed prograding shelf edge—the former sedimentary margin that advanced gradually into Lake Pannon—is based on Magyar et al. (2013).

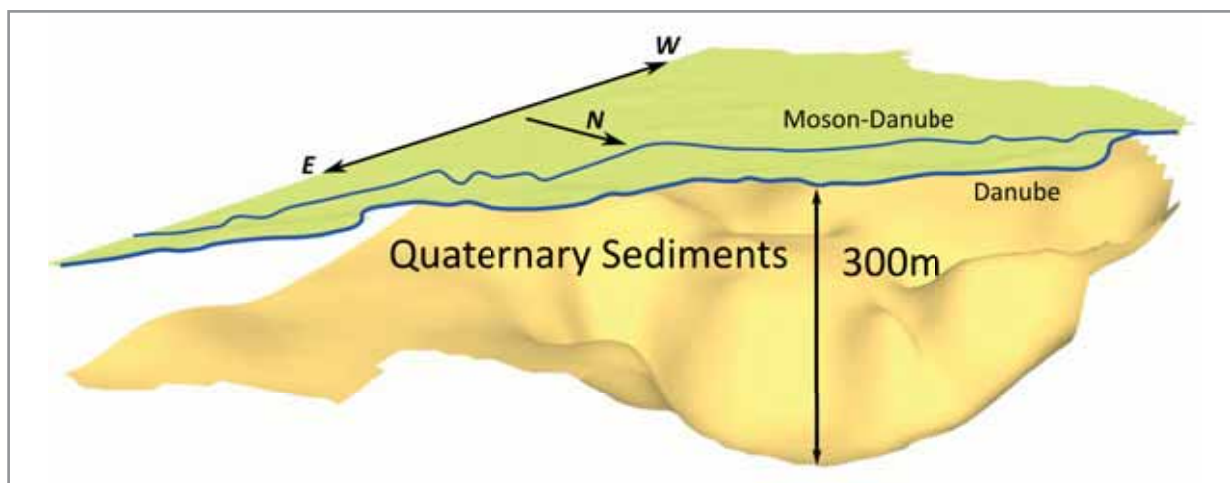


Figure 9: Depth of Quaternary sediments below Szigetköz. The surface represents the base of the sediment layer.

The sediment composition transitions from predominantly gravel in the west to increasingly finer-grained deposits towards the east (Szabó, 2005). Szigetköz is composed of sandy-gravel layers 20-400 meters thick, underlain by over 2,000 meters of Pannonian sediment that stores significant amounts of water accumulated over geological time. The terrain, consisting mainly of low-lying, flood-prone plains, has remnants of ancient riverbeds visible in the landscape, influencing land use (Sharek et al., 2000)

1.3. Soils and land-water interactions

The soils of Szigetköz developed on alluvial deposits under the combined influence of climate, vegetation, flooding, and groundwater conditions (Várallyay, 2003). The parent material consists mainly of young sandy and silty deposits transported by the Danube, with gravel layers occurring at varying depths. Soil-forming processes therefore differ according to local hydrological conditions. Meadow soils are characteristic of areas with a shallow groundwater table but without regular flooding, whereas chernozem formation occurs where groundwater lies deeper.

The alluvial soils of the Danube floodplain generally have a light texture. Sand, sandy loam, and sandy silt predominate, while silt, loam, and silty loam occur less frequently. These soils are alkaline, with pH values generally ranging from 7.8 to 8.3, and contain surface carbonates, typically 10-25% CaCO_3 . Their high carbonate content and mineral composition give them a pale greyish-brown color, which is lighter than might be expected from their moderate organic-matter content of approximately 1.5–3.0%. This relatively pale color remains characteristic even after the development of a humus-rich surface layer. The hydrological properties of these alluvial soils depend primarily on soil texture, water-holding capacity, the depth of the gravel layer, and the potential for capillary water supply from groundwater. The most favorable conditions occur where soils have a medium texture, a deep productive layer, and groundwater remains within or close to the overlying

fine-grained deposits. Where gravel occurs close to the surface, available soil-water storage decreases, and soils become more susceptible to drought (Szabó M., 2005). This relationship means that similar changes in river or groundwater levels may have different effects over relatively short distances. Where the soil cover is sufficiently deep and capillary connection with groundwater is maintained, groundwater can contribute to plant-available moisture. In areas with shallow gravel or limited capillary contact, vegetation and crops depend more strongly on precipitation and are therefore more exposed to dry periods.

In addition to alluvial soils, Szigetköz contains patches of marsh-meadow and alluvial meadow soils, where meadow and pasture management is typical. Floodplain deposits immediately adjacent to the river channels support marshy meadows, tussock-forming wetland vegetation, floodplain meadows, and shrubby willow communities. In the Rajka area, small patches of sandy alluvium occur over more extensive areas of carbonate-affected chernozem. Agricultural production in Szigetköz takes place mainly on terrace chernozems, humus-rich alluvial soils, alluvial meadow soils, and meadow soils (Szabó M., 2005). The spatial distribution of the main soil-texture classes is shown in Figure 10.

Former channel migration, channel incision, sediment deposition, and the abandonment of individual river branches created highly heterogeneous soil conditions. As a result, soil texture, profile thickness, gravel depth, and water-retention properties may vary over distances of only a few meters. Figure 11a shows the surface expression of former channel patterns in agricultural fields, while Figure 11b presents an electrical-resistivity profile on the landward side of a flood-protection levee. The repeated subsurface zones visible in the profile indicate the presence of successive channel deposits and abandoned channel forms.

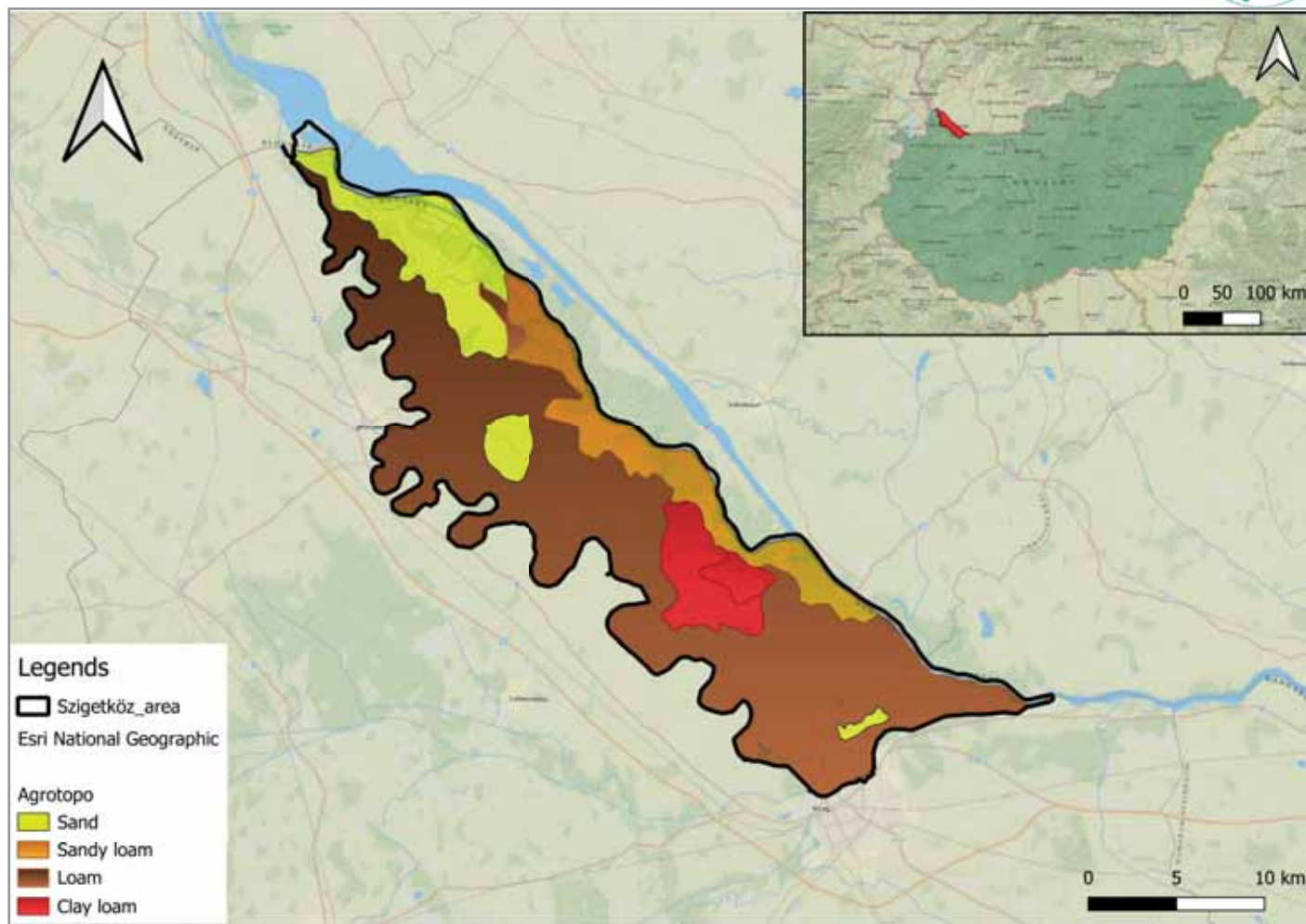


Figure 10: Generalized soil-texture distribution in Szigetköz. Source: Agrotopographic Database (Agrotopo), based on data from the Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences (2009)

These soil–water interactions are directly relevant to floodplain rehabilitation. Changes in surface-water levels and groundwater conditions influence soil moisture, vegetation, forestry, agricultural productivity, and drought sensitivity, but the response depends on local soil and sub-surface conditions. Consequently, groundwater levels and soil moisture must be considered alongside surface-water conditions when evaluating the effects of water replenishment. Both are included among the Szigetköz system’s monitoring components.

1.4. Hydrology, groundwater and water quality

Szigetköz is situated on the Danube’s alluvial fan in the Hungarian Little Plain, where coarse sediments were deposited in a broad, fan-shaped pattern. This geomorphological setting is closely related to the river’s longitudinal profile. The longitudinal profile shows a major regional change in channel gradient near river kilometer (rkm) 1950 and a further decrease across the Szigetköz reach, from approximately 0.43‰ near rkm 1860 to approximately 0.17‰ near rkm 1800 (Figure 12).

This reduction affects flow velocity, sediment transport and deposition, and the development and lateral movement of river channels. Together with later human interventions, including channel regulation, barrages, branch closures, and flood-protection levees, the change in gradient continues to influence the hydromorphological and ecological functioning of Szigetköz.

The decrease in channel slope promoted sediment deposition from the upper Danube (Figure 12). At the upstream part of the alluvial fan, repeated sediment deposition, erosion, channel migration, and the formation of bars and islands produced an extensive network of interconnected river branches. This wider, multi-channel floodplain system is commonly described as an inland delta, while Szigetköz itself is the large river island situated between the Old Danube and the Mosoni-Danube.

Before large-scale river regulation, the Danube migrated across the alluvial fan through a continuously changing branch system. The distribution of water among the main channel, side branches, floodplain water bodies, and the underlying aquifer created a close relationship between surface-water and groundwater conditions.

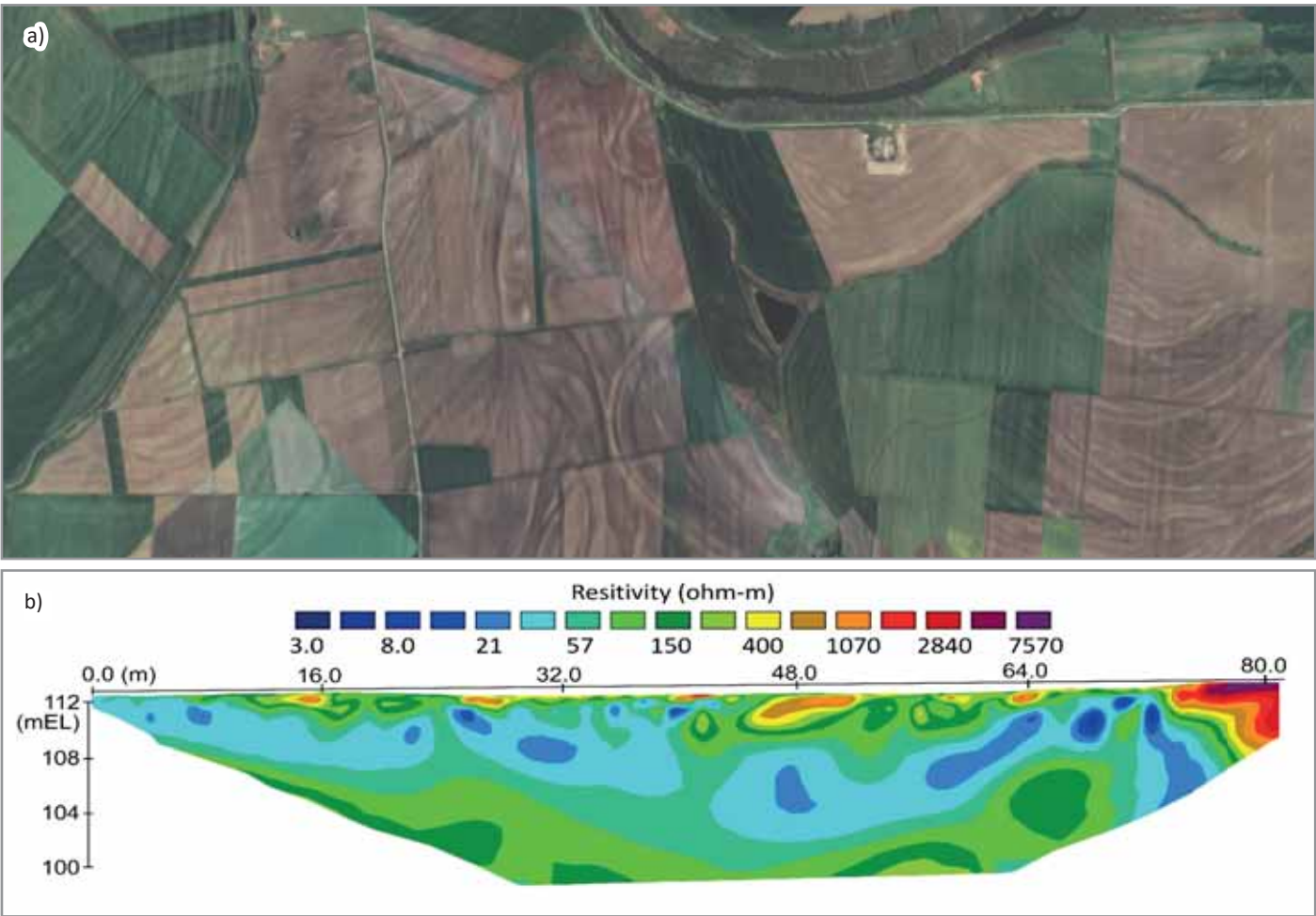


Figure 11: a) Surface expression of former channel-cutting and depositional patterns in agricultural fields; the image has been sharpened to emphasize the features; b) Electrical-resistivity profile on the landward side of a flood-protection levee, showing comparable former channel features in cross-section

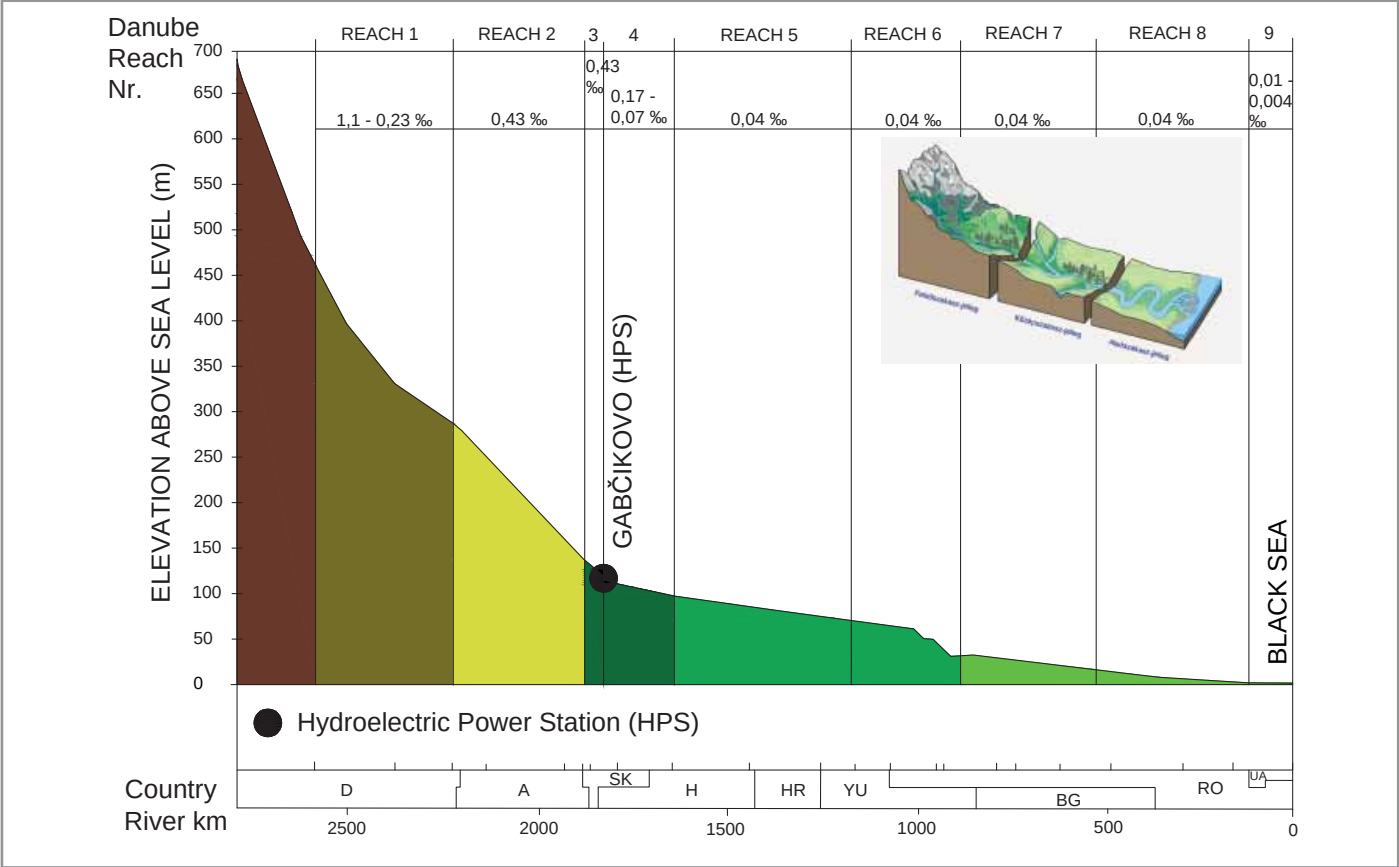


Figure 12: Longitudinal profile of the Danube showing the major regional change in channel gradient near rkm 1950 and the lower-gradient reach toward Szigetköz

Consequently, the water balance of Szigetköz remains strongly dependent on the hydrological regime of the Danube.

The river's seasonal flow regime is influenced predominantly by its Alpine catchment. Discharges generally increase during spring and early summer due to snowmelt and rainfall, while lower flows are more characteristic of autumn and winter. Median monthly discharges at Bratislava are shown in Figure 13. Depending on hydrological conditions and location along the river, annual water-level fluctuations may range from approximately 4 to 8 m. These fluctuations historically maintained changing patterns of inundation, channel connectivity, sediment movement, and habitat availability within the active floodplain. The remaining labyrinth of side branches therefore supports a range of flowing, slow-flowing, and temporarily connected aquatic habitats (Guti, 2020).

Szigetköz features a highly dynamic groundwater system closely tied to the Danube River's hydrology. The interaction between surface water (from the Danube, Mosoni-Danube, and floodplains) and the permeable sediments of the alluvial plain governs the area's groundwater flow. Coarse-grained sediments, gravels, and sands compose the alluvial fan, which has a high hydraulic conductivity, allowing rapid infiltration and groundwater movement. The unconfined aquifer system responds quickly to changes in river stages, precipitation, and anthropogenic influences, such as river regulation.

Before major river regulation and diversion, groundwater levels broadly followed the seasonal dynamics of the Danube. Higher river stages promoted recharge from the river towards the aquifer, while lower stages could reverse or weaken the hydraulic gradient. This interaction supported soil moisture, wetlands, floodplain forests, and agricultural land beyond the immediate river channels.

Hydrological alterations have also affected sediment transport and water quality. Reduced sediment supply, channel incision, fine-sediment deposition, and changes in flow velocity and water residence time influence channel morphology, hydraulic connectivity, oxygen conditions, nutrient processes, and aquatic habitats. Water quality in the floodplain system is therefore determined not only by the quality of the Danube water entering Szigetköz, but also by local hydraulic and ecological conditions.

Hydrology, groundwater, sediment dynamics, and water quality must consequently be considered as interacting components of a single system. The following chapters describe how these conditions changed, which water-replenishment measures were implemented, and how their effects were evaluated through hydrological, water-quality, and biological monitoring.

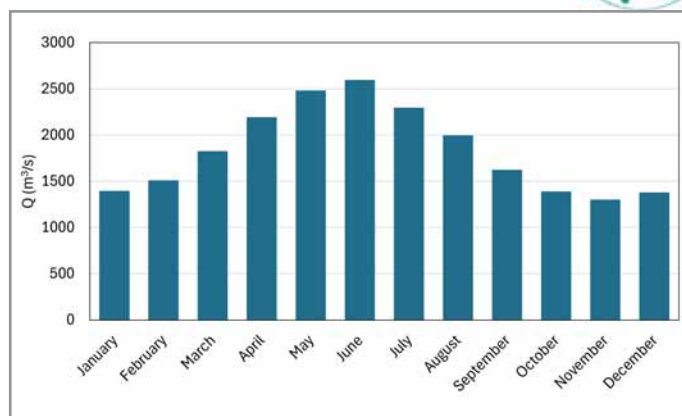


Figure 13: Median monthly discharges of the Danube at Bratislava (Dévény) by calendar month

1.5. Climate and climate change

1.5.1. Present climate

The Szigetköz region has a moderately warm, moderately dry transitional climate, characterized by mild winters. Although its geographic location allows some Atlantic influence, the Carpathian Basin's enclosed setting reinforces continental climatic characteristics. The region consequently experiences considerable temperature variability, an uneven seasonal distribution of precipitation, and recurrent droughts (Szabó, 2005). Mean January temperatures range between approximately -1 and -2 °C, and the region experiences around 90–100 frost days annually. Mean July temperatures range between 19 and 22 °C, with approximately 60–65 summer days and 10–15 hot days per year.

Annual precipitation generally ranges between 600 and 650 mm in the western part of the region, compared with less than 550 mm in the eastern part of the Carpathian Basin. Precipitation is more evenly distributed than in the Great Hungarian Plain and typically peaks in early summer.

Wind is also an important climatic factor. Szigetköz is one of Hungary's windier regions, with mean wind speeds of approximately 2.0–3.5 m/s and prevailing winds from the northwest. Snow cover occurs on approximately 40–50 days per year and generally reaches a maximum depth of 20–30 cm. Long-term meteorological change is illustrated by the annual and decadal temperature and precipitation anomalies for northwestern Hungary shown in Figure 14.

The anomalies represent deviations from the mean temperature and precipitation calculated for the 1952–2022 reference period. They were derived by subtracting the overall mean annual temperature of 10.45 °C and mean annual precipitation of 652 mm from the corresponding annual or decadal values.

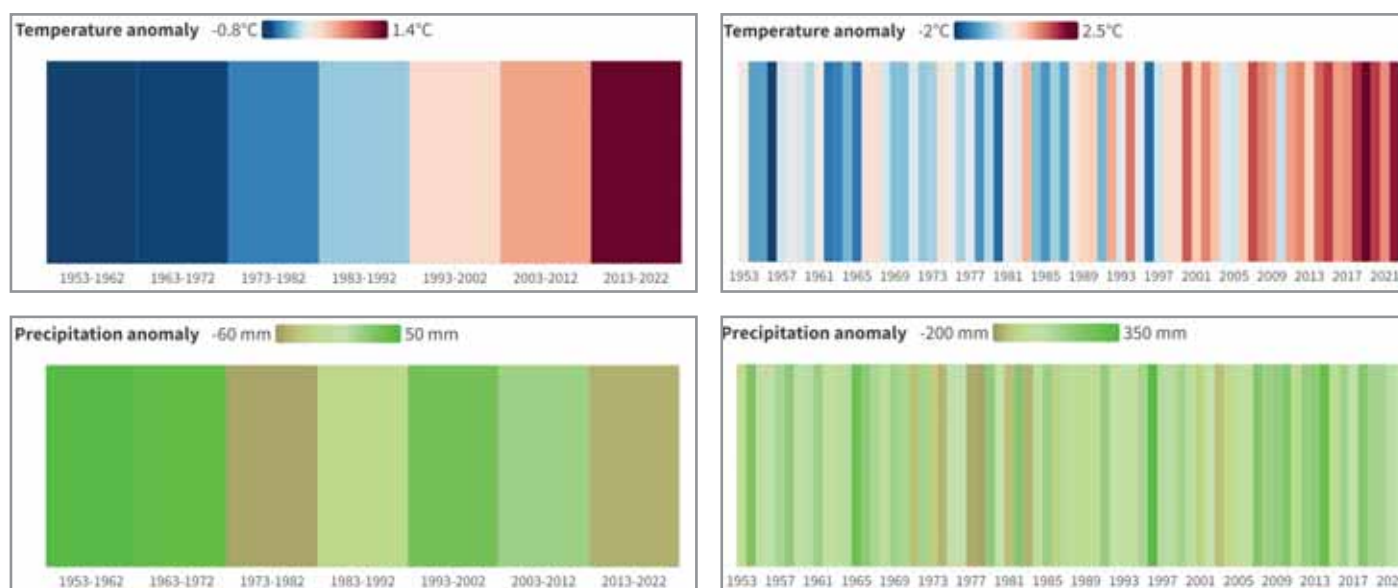


Figure 14: Temperature and precipitation anomalies in northwestern Hungary

Both annual and decadal temperatures show a rising trend, consistent with wider climatic warming, while precipitation displays pronounced interannual and decadal variability, with alternating wetter and drier periods. The combination of relatively low precipitation, warm summers, and persistent winds results in a negative mean annual climatic water balance, with an estimated deficit of approximately 50–75 mm. The Danube and its branch systems partly moderate these regional conditions by creating a more humid floodplain mesoclimate. Areas with higher air and soil moisture provide favorable conditions for riparian habitats and floodplain forests, including oak-dominated communities, despite the generally dry regional climate (Szabó, 2005).

1.5.2. Climate change

Meteoblue prepared a climate-related risk assessment for the Szigetköz DALIA demonstration site, DPS1 (Meteoblue, 2024). The assessment considered 29 climate dimensions grouped into four categories: temperature, wind, water, and solid matter. Conditions in the reference period, defined as the current climate (2015–2034), were compared with projected conditions for 2031–2050.

The projections were based on IPCC global climate-model outputs and ERA5 reanalysis data, statistically down-scaled to represent local conditions. Four emissions scenarios were considered: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The summary risk classification presented here is based primarily on SSP5-8.5, with RCP8.5 results used where indicated in the original assessment.

Risk levels were determined from the estimated probability that projected climatic values would exceed the corresponding mean values of the reference period.

Temperature-related hazards form the most prominent part of the future risk profile. Changing air temperature, heat stress, and heat waves are classified as Medium risk under the SSP5-8.5 scenario. Heat stress is expected to increase from the current Low risk classification to Medium risk in the future. Temperature variability and wildfire remain classified as Low risk, while the risks associated with cold waves and frost are projected to decline. Freshwater temperature changes and permafrost thawing are classified as presenting no significant risk at this location.

Wind-related risks are generally low or absent. Changing wind patterns and windstorms are classified as no risk in both the current and future periods. Future risks associated with tornadoes, blizzards, dust storms, and sandstorms could not be fully evaluated because of insufficient data.

Most assessed water-related hazards are also classified as presenting no direct risk at the DPS1 location. These include changes in precipitation patterns, hydrological variability, water stress, heavy precipitation, and flooding within the assessment framework. Drought is the principal exception: it increases from No risk under current conditions to Medium risk under the future SSP5-8.5 scenario. Sea-level rise, saline intrusion, ocean acidification, and glacial-lake outburst floods are not relevant to the Szigetköz region. Within the solid-matter category, soil erosion and solifluction are classified as No risk, while soil degradation could not be evaluated because of insufficient local data. Subsidence is the only solid-matter hazard assigned a notable classification and is assessed as Medium risk under both current and future conditions. The results are summarised in Figure 15.

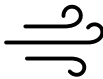
				
	Temperature-related climate risks	Wind-related climate risks	Water-related climate risks	Solid matter-related risks
Chronical	Changing air temperature	Changing wind patterns	Changing precipitation patterns: rain	Coastal erosion
	Changing freshwater and marine water temperature		Changing precipitation patterns: hail	Soil degradation
	Heat stress		Precipitation or hydrological variability	Soil erosion
	Temperature variability		Ocean acidification	Solifluction
	Permafrost thawing		Saline intrusion	
			Sea level rise	
			Water stress	
Acute	Heat wave	Windstorm (incl. cyclone, hurricane, and typhoon)	Drought	Avalanche
	Cold wave / frost	Blizzards, dust, and sandstorm	Heavy precipitation	Landslide
	Wildfire	Tornado	Flood (coastal, fluvial, pluvial, ground water)	Subsidence
			Glacier lake outburst	
No data No risk Low risk Medium risk High risk Red flag				

Figure 15: Summary of the climate risks for the 29 climate dimensions within the four categories “temperature”, “wind”, “water” and “solid matter” for the location DPS1 (Hungary) for 2015 to 2034 (current) and 2031–2050 (future) with SSP5-8.5 and RCP8.5 emission scenario (where available; discrepancies mentioned in the respective climate dimension subchapters). Only higher risk classes from current and future risks are shown in this table

Overall, the assessment indicates low direct exposure to most of the evaluated climatic hazards, while identifying moderate risks associated primarily with rising air temperature, heat stress, heat waves, drought, and land subsidence. The combination of rising temperatures and drought risk is particularly relevant in a region with a negative climatic water balance. It may increase pressure on soil moisture, groundwater-dependent habitats, floodplain forests, agriculture, and the allocation of water among ecological and socio-economic uses. The risk classifications should therefore inform the adaptive management of the water-replenishment system. Long-term planning should consider not only individual climate hazards but also their combined effects on water availability, seasonal water demand, ecological water requirements, and the resilience of floodplain habitats. Indirect effects on infrastructure, economic activity, and supply chains may also occur even where the assessment assigns a low or no direct climatic risk.

1.6. Historical land use, habitats, and protection

Historically, the hydrological conditions of Szigetköz favored extensive livestock farming. Frequent flooding and high groundwater levels limited widespread arable cultivation, while meadows, pastures, forest clearings, and seasonally inundated areas provided suitable grazing land. Extensive livestock husbandry in the region can be traced back to at least the thirteenth century. Settlements were generally established on higher ground, including former islands, elevated floodplain surfaces, forest clearings, and breaks within meadow areas. Land use around the villages typically followed a spatial sequence of gardens and orchards, arable fields, meadows, pastures, and forests. This pattern reflected local differences in elevation, flood exposure, groundwater conditions, and soil properties.

During the late nineteenth century, changes in river regulation, flood protection, and agricultural practices transformed the regional farming system. Livestock production became more intensive, and animals were increasingly kept in stables rather than grazed extensively. Crop rotation gradually replaced fallow systems, while maize cultivation expanded as drainage and flood protection created more favorable conditions for arable agriculture (Figure 16). Agricultural intensification continued during the twentieth century. By the 1980s, herbicides were applied to approximately 91% of arable land, while nearly 30% of cultivated areas received additional plant protection during the growing season.



Figure 16: Farming around 1935

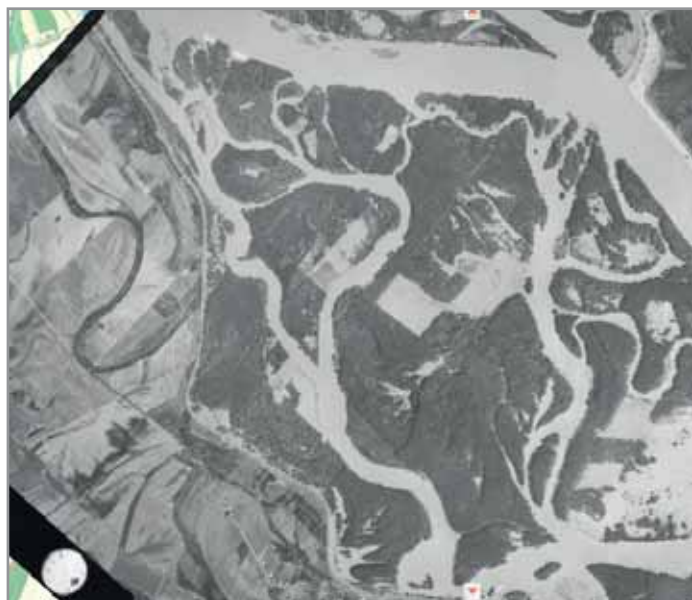


Figure 17: Floodplain near Ásványráró in 1965 and 1993 (fentrol.hu)

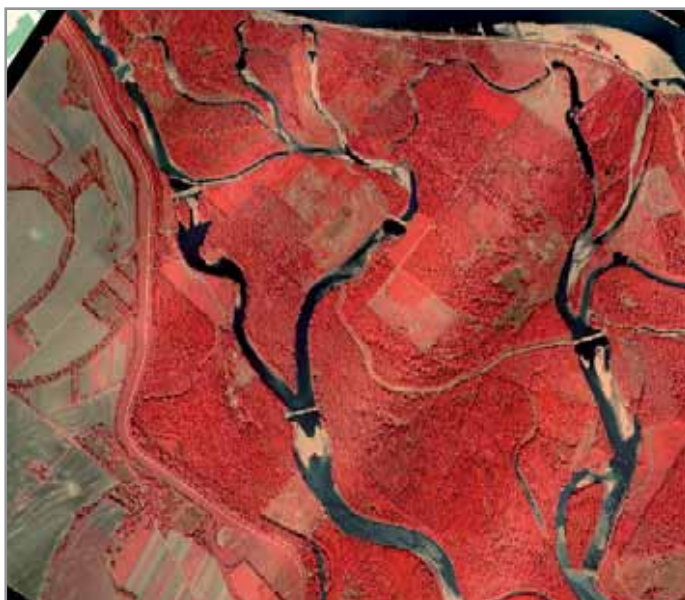
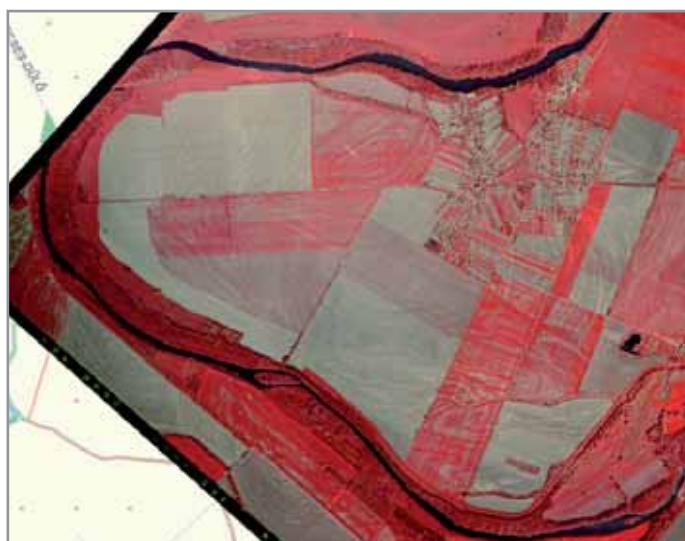


Figure 18: Floodplain of the Mosoni-Danube near Dunaszeg in 1965 and 1993 (fentrol.hu)



Mineral fertilizers introduced substantial quantities of nitrogen, phosphorus, and potassium into agricultural soils. By the end of the twentieth century, changes in land ownership, agricultural organization, and market conditions contributed to a marked decline in livestock farming. Alongside drainage and flood protection, irrigation gradually became a supplementary means of stabilizing agricultural production during dry periods, although precipitation and groundwater conditions remained the dominant controls on regional water availability. Forestry in Szigetköz remained largely unmanaged for a long time, with local communities depending on naturally regenerating floodplain forests for their wood supply. In the past, vast oak forests covered the region, but their last remnants were sold to timber markets in the 1880s (Szabó, 2005).

However, these oak forests were not continuous woodlands but were mainly found on higher ground, while shrub willows, willow-poplar floodplain forests, and sand-bank vegetation dominated lower-lying areas. Intensive forestry began in the 1920s, replacing natural forests with improved tree varieties for higher yields. By the 1950s, willows dominated, with poplars and hardwoods covering significant areas. The popularity of improved poplar varieties peaked in the 1980s, accounting for 68% of forested areas. This management suppressed natural forest communities, such as the willow-poplar-alder groves, and habitats for species like alder and elm-poplar groves de-

clined. In the 1990s, a shift toward near-natural forestry led to efforts to restore native tree species, though changes were modest. Most of the forests are located in the active floodplain and along the Mosoni-Danube, but smaller forest patches can be found throughout the region (Hahn et al., 2011). The changes in floodplain structure, vegetation, and forest cover near Ásványráró and Dunaszeg between 1965 and 1993 are illustrated in Figures 17 and 18.

The present historical floodplain is a mosaic landscape shaped by both former river processes and long-term human land use. Arable land is the dominant land-use category and covers approximately 55% of the area. Meadows and pastures account for about 10%, while forest strips, canals, oxbow lakes, marshes, reedbeds, other wetlands, and open-water areas together constitute a further approximately 10%. More than 20 settlements occupy around 8% of the historical floodplain. The current land-use pattern is shown in Figure 19.

Faunal diversity is high for a landscape of this size. The fish fauna comprises approximately 80% of Hungary's native species, encompassing stream specialists and wetland taxa. Amphibians are well represented, while reptiles are fewer in number and include the grass snake and the European pond turtle. Around 230 bird species are recorded. Herons and cormorants breed in colonies, and several strictly protected raptors and waders are present.

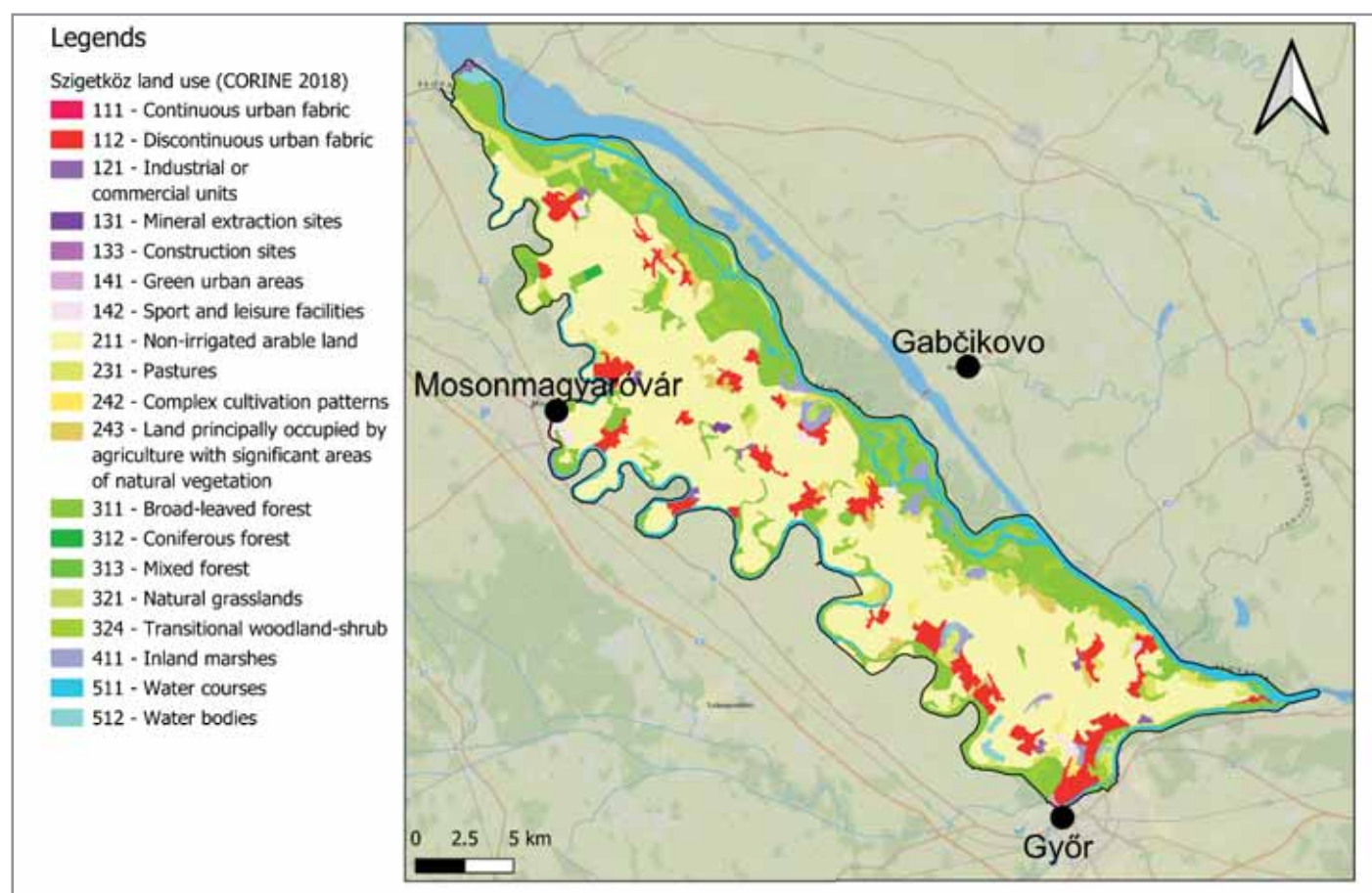


Figure 19: Szigetköz land use

Winter brings large flocks of dabbling and diving ducks. Among mammals, the stoat, pine marten, several bat species, and the resurgent Eurasian beaver are characteristic, and a glacial-relict vole persists locally (Fertő Hanság Nemzeti Park). Examples of flora and fauna are shown in Figure 20.

The ecological value of the region is closely connected to the coexistence of flowing and slow-flowing channels, oxbows, periodically inundated habitats, wet meadows, softwood and hardwood floodplain forests, agricultural areas, and smaller habitat elements embedded within the cultivated landscape. The resulting biodiversity therefore depends not only on formally protected areas but also on the hydrological and ecological connectivity of the wider landscape.

The Szigetköz Landscape Protection Area was established in 1987 to conserve the region's characteristic hydrological system, habitats, flora, and fauna. It currently covers approximately 27% of Szigetköz and includes several strictly protected areas distributed among two larger and several smaller mosaic units. Parts of the Landscape Protection Area overlap with the Natura 2000 network, while Natura 2000 designation also extends beyond the nationally protected areas (Figure 21).

The overall conservation objective is to maintain or restore the favorable conservation status of the species and habitat types of Community interest for which the sites were designated. Achieving this conservation objective requires the maintenance of the natural conditions that support these species and habitat types, as well as land- and water-management practices compatible with their long-term protection. The wider extent of Natura 2000 protection across the floodplain is illustrated in Figure 22, while Figure 23 shows that the protected landscape includes both agricultural areas and floodplain habitats.

The present landscape should therefore not be interpreted as either an undisturbed natural floodplain or an exclusively agricultural production area. It is a historically developed socio-ecological mosaic in which agriculture, forestry, settlements, water management, and protected habitats occur within the same hydrologically connected system. Rehabilitation and conservation measures must consequently address not only individual protected sites but also the water regime, habitat connections, and land-use practices that maintain ecological functions across the active and historical floodplains.



Figure 20: Flora and fauna of Szigetköz

a) wet meadow; b) floodplain branch with reeds and forest; c) fox in floodplain vegetation; d) great egret in the active floodplain branch system

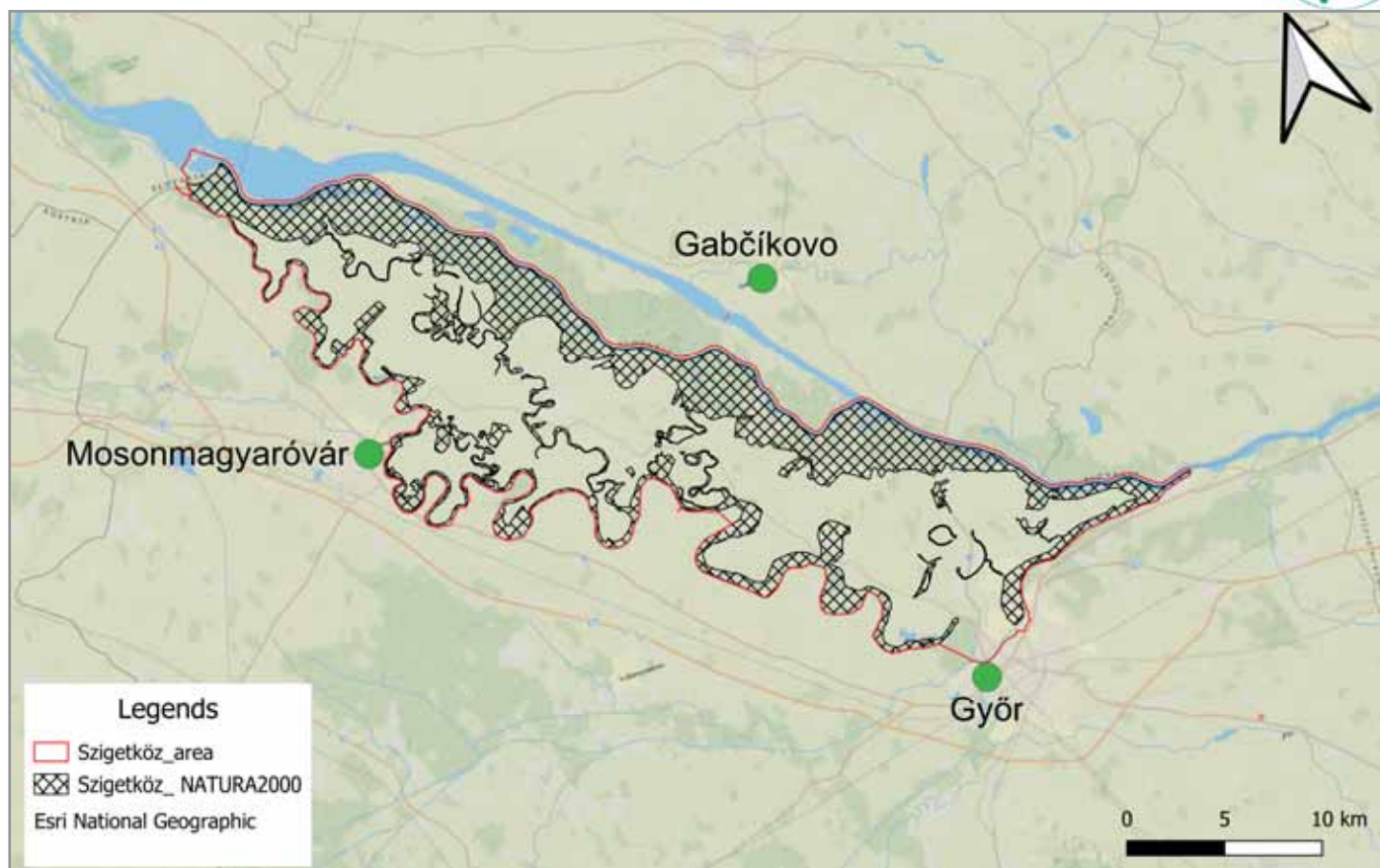


Figure 21: Szigetköz Natura 2000 protected areas



Figure 22: The whole floodplain is now under Natura 2000 protection (Fertő–Hanság National Park)

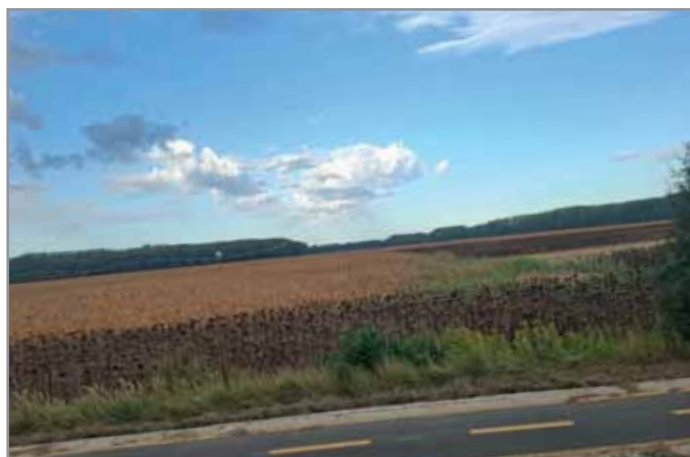


Figure 23: Both agricultural and floodplain areas are protected

1.7. Ecosystem services and competing water uses

Ecosystem services are the benefits that people obtain from functioning natural systems. In Szigetköz, these benefits arise from the close connection between the Danube, its side branches, groundwater, soils, floodplain forests, wetlands, and the communities that use and manage them. The ecosystem-services concept provides a practical way to describe how ecological condition is linked to human well-being and economic activity (Millennium Ecosystem Assessment, 2005; TEEB, 2010; Haines-Young and Potschin, 2018).

The most important provisioning services, meaning material benefits used directly by society, include drinking-water resources, agricultural products, timber, fish, and other locally produced goods. The thick gravel aquifer beneath Szigetköz stores substantial groundwater resources, while the river and groundwater system also influence soil moisture and the productivity of agricultural and forested land. Fisheries and recreational angling depend on suitable water quality, adequate flow, and connected aquatic habitats.

Regulating services include groundwater recharge, the storage and movement of water, the moderation of local climatic conditions, and the retention or transformation of nutrients and sediments. Floodplain areas can temporarily store water and slow its flow, though present-day flood protection also depends heavily on levees, drainage systems, pumping stations, and other engineered infrastructure. Wetlands, side branches, and floodplain vegetation contribute to water-quality regulation and provide habitats that support the ecological functioning of the wider river system.

Szigetköz also provides important cultural services. Its rivers, wetlands, forests, and characteristic landscape support recreation, fishing, canoeing, kayaking, cycling, bird-watching, environmental education, and nature-based tourism. The landscape also contributes to regional identity, aesthetic value, local traditions, and cultural heritage. These benefits are less easily expressed in physical or monetary terms, but they remain important to both residents and visitors.

Biodiversity and functioning habitats underpin all these services. Diverse aquatic and terrestrial communities contribute to food webs, nutrient cycling, natural regeneration, and the floodplain's ability to respond to environmental change. Biodiversity should therefore be understood not only as a conservation objective but also as part of the ecological foundation on which many social and economic benefits depend.

The different uses of water do not always require the same conditions. Drinking-water supply depends on reliable groundwater recharge and the protection of water quality. Agriculture may require sufficient soil moisture but also protection from prolonged waterlogging. Floodplain forestry and wetland habitats benefit from periodic inundation, while settlements and infrastructure require effective flood protection. Fish populations depend on seasonal water-level changes and connected habitats, whereas recreation and tourism often favor safe access and predictable water conditions. Nature conservation may also require restrictions on access or particular operating conditions in sensitive areas.

Water management must therefore balance several legitimate but sometimes competing interests. Maximizing one benefit—for example drainage, permanently high water levels, timber production, recreation, or the rapid transfer of water—may reduce other ecological or social benefits. The purpose of integrated water management is not to optimize every use in isolation, but to identify operating conditions that maintain the floodplain's main ecological functions while supporting essential social and economic activities.

The Szigetköz water-replenishment system illustrates this multifunctional approach. Its planning and operation require ecological, drinking-water, flood-protection, agricultural, forestry, fisheries, recreational, and tourism interests to be considered together. Stakeholder participation, monitoring, and periodic adjustments to operating rules are therefore necessary to identify trade-offs and respond to changing hydrological and climatic conditions.

1.8. Cultural heritage

Szigetköz has a rich and diverse cultural heritage that reflects the region's long relationship with the Danube, its floodplain landscape, and its different ethnic and religious communities. Important architectural landmarks include the three-towered Hédervár Castle and its English landscape park, as well as the approximately 700-year-old Árpád Tree. The Calvary at Ásványráró is easily accessible from the EuroVelo cycling route. Several settlements preserve elements of everyday rural and industrial heritage. Kisbodak maintains the tradition of communal ovens, while Dunaszeg commemorates its former narrow-gauge railway. Kímle's location near the ancient Roman frontier, the Limes, adds a further historical dimension to local tourism. German and Croatian communities have also contributed to the region's linguistic diversity, customs, and traditions. Religious heritage includes the pilgrimage site at Máriakálnok and the Romanesque church at Lébény. Water-management structures also form an important part of the region's cultural and technical heritage.



Figure 24: Cultural heritage in Szigetköz: (a) Hédervár Castle and (b) The oldest English oak in Hungary; (c) Traditional Ovens of Kisbodak; (d) Patkányos Pump Station and Siphon

Pumping stations and related structures in Ásványráró, Győrzámoly, and other settlements are protected under national law and are increasingly included in tourism and educational initiatives. These sites demonstrate how local communities have adapted to floods, high groundwater levels, and changing river conditions. Figure 24 presents examples of architectural, community, and water-management heritage in Szigetköz.

Folklore associated with the former water world is preserved in local museums, exhibitions, and cultural centers. Recognized regional values include traditional crafts, gastronomy, folk customs, historic chapels, water-related heritage, and locally produced foods. The Szigetköz Regional Value Registry, established in 2020, documents cultural and natural assets in order to strengthen regional identity and support their long-term preservation. Registered values include the Győrzámoly Village Museum, heritage sites in Kimle, and various local monuments.

Festivals and community events also contribute to the visibility of the region's heritage. One example is the Mecsér Boat Festival, which connects local traditions with the river landscape. Cultural, sporting, and heritage associations play a central role in maintaining these activities.

Examples include the Halászi Preservation Society, the Dunaszegi Rezeda Folk Art Association, and theatrical groups in Dunakiliti.

Environmental education is another important part of local community life. Initiatives such as the Pisztráng Kör eco-school and educational programs in Kimle have gained recognition beyond the region. However, many civil organizations depend heavily on a small number of committed local leaders, creating challenges for continuity and for involving younger generations.

The cultural heritage of Szigetköz is therefore not limited to individual monuments. It includes buildings, water management structures, landscapes, traditions, community knowledge, and local organizations. Preserving these interconnected values can strengthen regional identity while supporting environmental education, sustainable tourism, and public understanding of floodplain rehabilitation.

2. EVOLUTION OF RIVER AND FLOODPLAIN TRANSFORMATIONS

This chapter outlines the historical transformation of the Szigetköz Danube reach, documenting how successive river regulations, navigation works, and hydropower developments progressively altered floodplain hydrology, morphology, and ecosystems. It distinguishes the effects of earlier interventions from those associated with the 1992 diversion of the Danube. This historical perspective helps explain present conditions and supports the definition of realistic rehabilitation objectives.



Figure 25: Tejfalusi branch system (Dunai 2024)



Transferable lesson 2 — Reconstruct the sequence of change before defining rehabilitation targets

Challenge addressed

Present-day floodplain degradation is usually the cumulative result of several interventions. River regulation, levee construction, channel closures, water diversion, sediment disruption, and land-use change may reinforce one another over decades or centuries.

Approach used in Szigetköz

The transformation of Szigetköz was reconstructed chronologically, from the former multi-channel floodplain through river regulation, flood-protection works, hydropower development, the 1992 diversion, and subsequent water-replenishment measures. This helped separate earlier structural changes from the effects of diversion and rehabilitation.

General principle

Reconstruct the sequence and cumulative effects of major interventions before defining reference conditions, rehabilitation objectives, and measures.

Evidence and operational relevance

Historical analysis showed that present conditions cannot be attributed to water diversion alone. Earlier regulation, levees, and channel closures had already altered flooding, connectivity, sediment transport, habitats, and land use. This supported the selection of realistic objectives and clarified which processes could be improved and which represented long-term constraints.

Conditions for transfer

Application elsewhere requires historical maps, hydrological and engineering records, land-use and ecological information, and local knowledge. Immediate impacts should be distinguished from longer-term changes in channels, groundwater, habitats, and land use.

Suggested indicators

Dates and extent of interventions; discharge distribution; flooding frequency and duration; channel creation or loss; riverbed and sediment changes; groundwater trends; land-use and habitat changes; and surface-water connectivity, water quality indices, biological indicator species.

Evolution of river and floodplain transformations

The regulation of the upper Danube in Hungary dates back to at least the 13th century, when early flood-prevention efforts, such as the construction of dykes, were documented. The Szigetköz section of the Danube, historically a dynamic system of wide and narrow free-flowing branches, was prone to frequent flooding, as recorded during the 18th century. Early interventions prioritized the construction of towpaths to facilitate inland shipping, which had to adapt continually to the river's shifting courses following flood events. By the 19th and early 20th centuries, river regulation efforts prioritized stabilizing the "Old Danube" as the main river. These measures included constructing levees and the Rajkai floodgate, which separated active and historical floodplains. These changes altered the region's hydromorphology, reducing the floodplain area and halting channel meandering. The expansion of levees limited floodplain activity, causing sediment to accumulate and raising flood levels. A network of drainage canals was built on the historical floodplain in the 1900s, connecting old oxbows and branches to the Mosoni-Danube to manage excess water.

Until the 1960s, the active floodplain branches still received water dynamically during floods. However, sediment deposition and navigation challenges increased over time. Following the 1960s, interventions such as groins temporarily stabilized the system. However, upstream barrages in Austria and Germany reduced sediment transport, leading to significant riverbed incisions. By the 1970s, declining bedload had intensified hydrological changes, prompting concerns about the river's long-term viability.

In response to these challenges, Hungary and Czechoslovakia agreed to the Gabčíkovo-Nagymaros Barrage Project in 1977 (Hungary and Czechoslovakia, 1977). The project aimed to generate hydropower, improve navigation, and enhance flood safety.

Plans included building a barrage at Dunakiliti, diverting water for hydropower generation, and replenishing the floodplain branches of the Szigetköz. However, by the 1980s, growing environmental concerns and public opposition in Hungary led to the suspension of construction of the Nagymaros barrage. In October 1992, Czechoslovakia implemented Variant C, diverting approximately 80% of the Danube's flow into the power canal serving the Gabčíkovo HPP.

The post-1992 flow reduction in the Old Danube was dramatic, with discharge near Rajka dropping by 80-90% and water levels falling by an average of 3 meters. This drop significantly affected groundwater, causing a 1.5-meter decline in the water table and disrupting local ecosystems, agriculture, and forestry. Drying floodplain branches in Upper Szigetköz led to habitat loss and environmental degradation, while those in Lower Szigetköz experienced increased riverbed incision and declining water levels over time. The changing condition of the Tejfalusi branch system before and after the introduction of water replenishment is illustrated in Figure 25.

Despite these impacts, the Mosoni-Danube benefited from a steady water supply, improving conditions during low-flow periods. The main sequence of river-regulation, diversion, and rehabilitation measures is summarized in Figure 26.

Between 1985 and 2023, a series of measures successfully restored water levels in the Mosoni-Danube and reestablished dynamic discharge fluctuations in active and historical floodplain river branch systems. These efforts, which prioritized ecological connectivity and active stakeholder involvement, underscore the importance of negotiation and compromise in achieving environmental restoration. The following sections provide a detailed overview of this system's planning, construction, and operation. Ultimately, while the regulations achieved flood control in Slovakia and improved shipping, they caused significant ecological and hydrological disruptions in the Szigetköz region, highlighting the trade-offs of intensive river management.

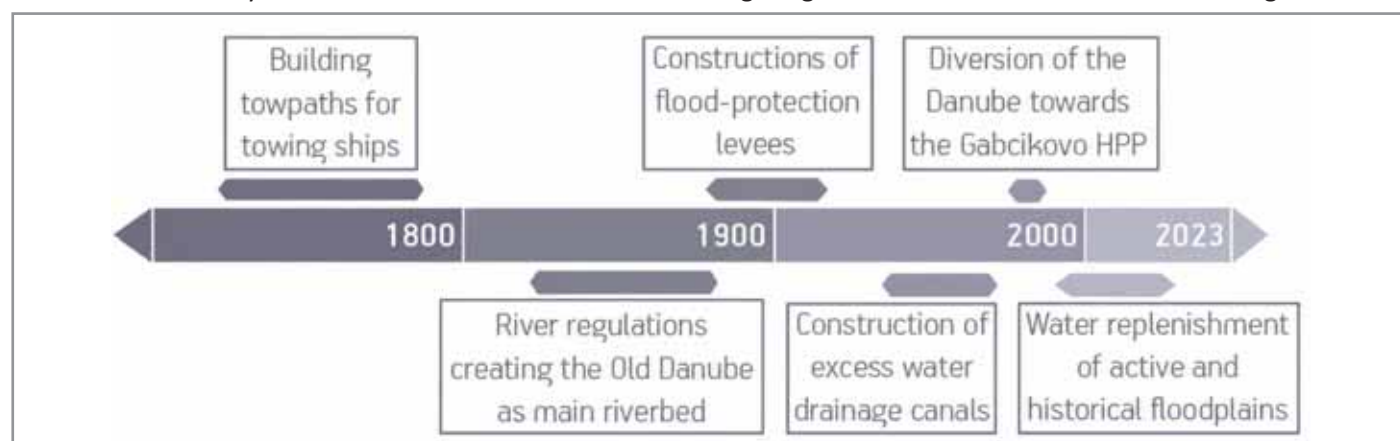


Figure 26: Timeline of the most significant anthropogenic alterations in the Szigetköz floodplain area between 1700 and 2023 (Chappon et al., 2024b)

The Church of Ásványráró – A Story Shaped by Water

According to medieval records, the church of Ásványráró stood before 1332 and was dedicated to Saint Andrew the Apostle. This dedication reflects the life of the village, where fishing was a primary livelihood and water was both a source of sustenance and a constant threat. Floods repeatedly damaged the building, and during the great floods of 1679–1680, the church suffered severe destruction. The extent of the damage is reflected in the 1681 will of Katalin Héderváry, who allocated funds not only for this church but also for others in the region, indicating the widespread impact of the disaster. The destruction did not end there. Another flood in 1700 again damaged the church, and it was only after years of restoration that it could be reconsecrated in 1703. Soon after, in 1719, a fire destroyed both the church and the parish building, leaving only the sacristy intact. Although caused by different forces, these events became part of a shared local memory in which water, fire, and rebuilding were closely intertwined. By the mid-18th century, the church was described as deteriorated, with a reed roof and repeatedly repaired walls. Floods continued to affect not only the structure but also the records of the community. During the major flood of 1830, several parish registers were damaged or lost, resulting in the disappearance of valuable historical information and collective memory. Despite repeated destruction, the church was always rebuilt. Each reconstruction reflected adaptation to local conditions, with raised sections, modified structures, and new additions responding to the presence of water. Over time, this process created a building shaped not only by faith but also by practical knowledge passed down through generations. Today, the church of Ásványráró stands as both a religious monument and a record of resilience. Its history illustrates how continuity in the Szigetköz does not mean permanence, but the ability to renew and adapt. The survival of the church reflects the persistence of the community that rebuilt it after every loss.

<https://asvanyraro.hu/latnivalok/>



2.1. Before 1800

The extent of the regularly flooded area before large-scale river regulation is shown in Figure 27. The reconstruction is based on the First Military Survey conducted between 1763 and 1785.

Regularly flooded area (light blue color) along the Szigetköz section of the Danube before the extensive river regulations based on the first military surveys carried out between 1763 and 1785. With the spread of steam shipping, the most important water management actions were designed to enable shipping. Since the Szigetköz naturally had many wide and narrow free-flowing branches that changed with every major flood event, new shipping routes had to be found to adapt to these conditions. The first intervention was the construction of towpaths for inland shipping in the 17th and 18th centuries.

2.2. 1800–1900

During the nineteenth century, river-regulation works increasingly concentrated the flow of the Danube into a principal channel, now known as the Old Danube. The main objectives were to improve navigation, stabilize the shipping route, and reduce the effects of frequent channel migration. Training structures were constructed to guide the flow and limit lateral movement, while individual branches were closed or partially separated from the main

channel. The regulation works progressively changed the hydromorphological character of Szigetköz. Flow became more concentrated in the Old Danube, while the frequency and duration of water exchange between the main channel and some side branches declined. Flood-protection works also began to restrict the area directly influenced by regular flooding. By the end of the nineteenth century, these interventions had established the basis for the more extensive levee and drainage systems developed during the early twentieth century.

2.3. 1900–1959

Following the First World War, the thalweg—the line connecting the deepest points of the principal river channel—was designated as the national boundary between Hungary and Czechoslovakia along much of the Szigetköz reach.

During the early twentieth century, flood-protection levees were completed and strengthened on both sides of the river. The levees formally separated the active floodplain between the embankments from the historical floodplain behind them. The Rajka floodgate and ship lock, later also known as the Trianon Lock, were constructed between 1905 and 1908 to regulate the supply of water from the Danube to the Mosoni-Danube. The levees substantially reduced the frequency of direct flooding in settlements and cultivated areas. However, they did not eliminate flood risk, seepage, high groundwater, or the accumulation of excess inland water behind the levees.

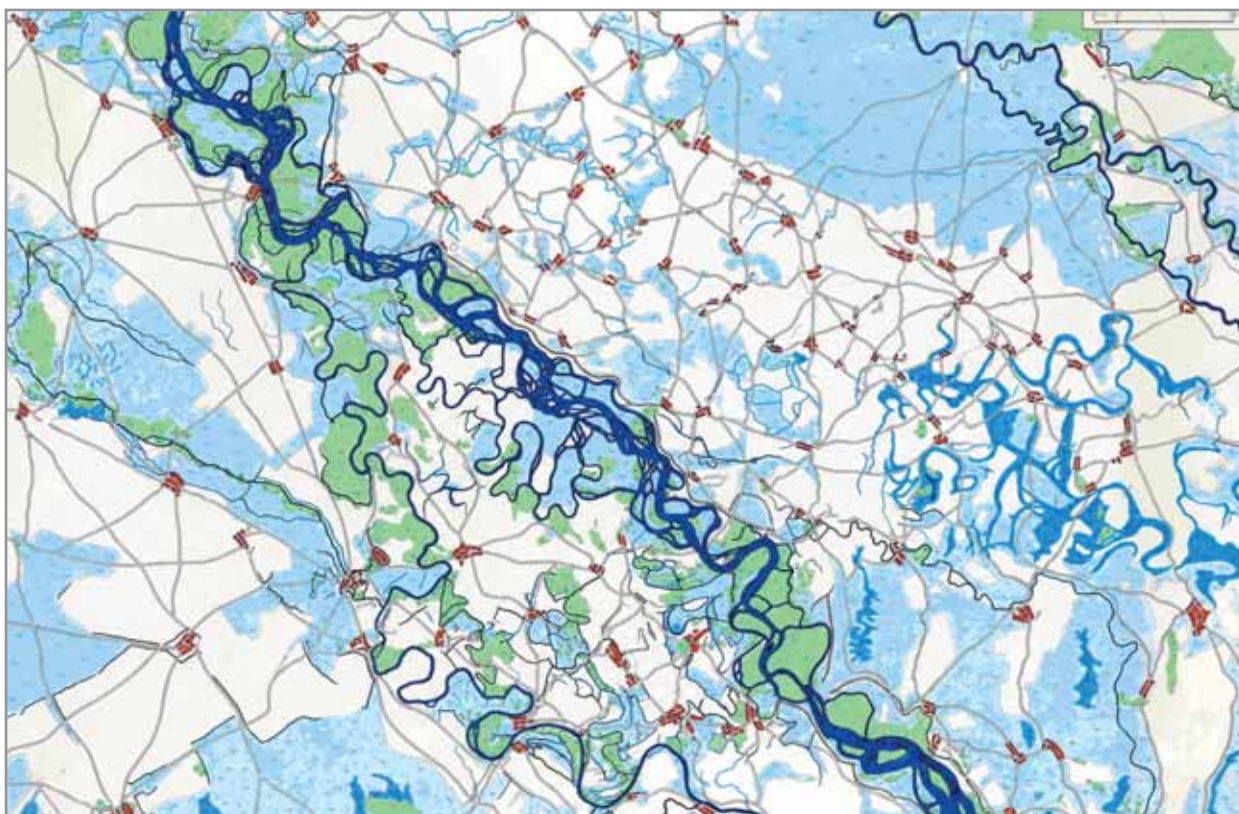


Figure 27: Extent of regularly flooded areas along the Szigetköz reach before large-scale river regulation, reconstructed from the First Military Survey conducted between 1763 and 1785. (SEA, 2010), based on material from the collection of the Danube Museum

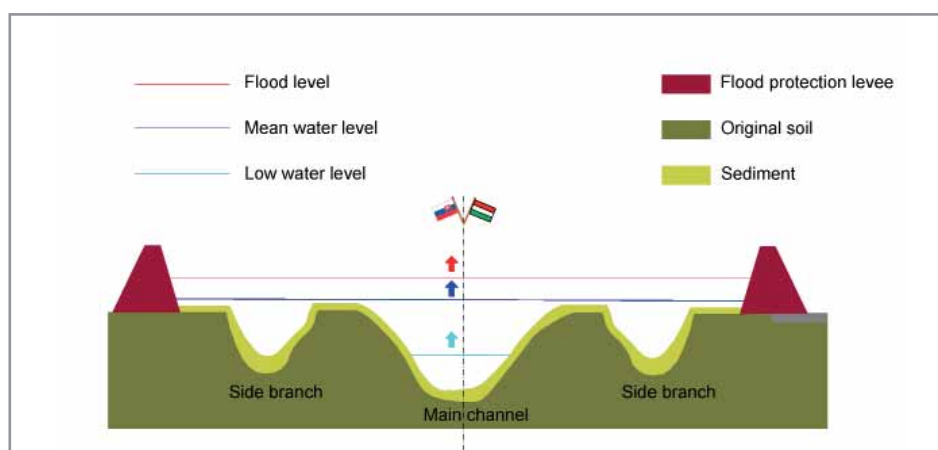


Figure 28: Water level and morphological changes until 1959

The July 1954 flood was a major turning point in the development of flood protection in Szigetköz. Severe flooding and failures in the existing defense system demonstrated the need for stronger and more consistent protection. Subsequent measures included raising and reinforcing levees, improving sections affected by seepage, and introducing a more systematic approach to flood-defense planning.

Due to levee construction, suspended sediments accumulated on the floodplain, significantly reducing its active area and leaving a large portion inactive. The reduction in the active floodplain area led to increased flood levels, necessitating the heightening and strengthening of the levees. As a result, during floods, higher water levels in the Danube led to increased seepage, resulting in greater volumes of excess water in the inland areas.

To manage this excess water, drainage canals and pumping stations were constructed across the historical floodplain during the twentieth century. Many drainage canals were created by connecting former oxbows and inactive Danube branches. The canal network generally follows the natural northwest-to-southeast slope of the terrain and conveys water toward the Mosoni-Danube at the southern end of Szigetköz.

Many canals retained water even after the flood-protection levees had been constructed because the permeable gravel deposits beneath Szigetköz allowed seepage from the Old Danube. The amount of water present nevertheless varied according to Danube stage, groundwater levels, local topography, and the operation of the drainage system. Careful operation of the canals and pumping stations was particularly important in Upper Szigetköz, where the fine-grained soil cover above the gravel deposits is often shallow. Groundwater had to remain sufficiently close to the land surface to support soil moisture and agricultural production. When groundwater levels declined, the thin soil layer could dry out rapidly, increasing the risk of water stress for crops.

During the 1950s, the Danube still maintained a dynamic connection with the active floodplain, and flow was distributed between the Old Danube and the active floodplain branches (Figure 28).

More problems arose for navigation in the Old Danube. During low and mean flow periods, large bed loads still reached the Szigetköz from the upper Danube, where they were deposited in the river and its branches, as the slope decreased significantly here. This process made it difficult to maintain the shipping route in the Szigetköz. Groins were constructed to raise water levels for shipping and reduce sediment deposition.

2.4. 1960–1992

During the middle and second half of the 20th century, many barrages were constructed in the upper Danube catchment in Germany and Austria. One of the significant consequences of these constructions was the reduced bedload transport in the Danube.

Bedload supply entering the Rajka reach of the Danube was estimated at approximately 650,000 m³/year during the 1960s, and by around 1990, the estimated bedload supply had declined to approximately 200,000 m³/year (Rákóczi, 1989). The decline was associated primarily with sediment retention by upstream barrages in Germany and Austria. Reduced bedload supply contributed to progressive riverbed incision during low- and medium-flow conditions, while suspended sediment continued to accumulate in parts of the active floodplain during floods. Industrial gravel dredging intensified the imbalance by removing additional material from the channel. As the bed of the Old Danube became lower relative to the beds of the floodplain branches, water entered those branches less frequently and at progressively higher Danube discharges.

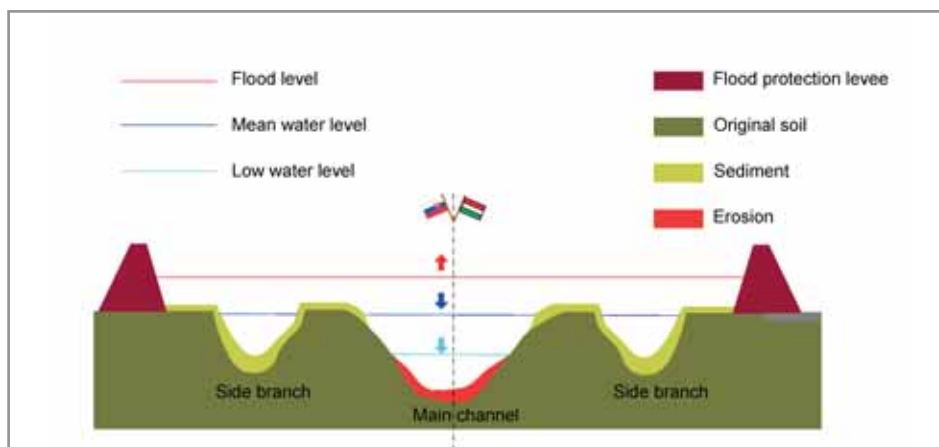


Figure 29: Water level and morphological changes after 1959

The side branches (in the upper active floodplain) were closed with parallel weirs and sluice gates to raise water levels in the Old Danube during low- and mean-flow periods, thereby ensuring shipping security. If the river discharge in the Danube was below 2000 m³/s (later 2500 m³/s because of riverbed incision), the active floodplain river branch system did not receive flowing water.

The side branches were still covered with water during these periods due to the high seepage rate from the Old Danube. By 1990, the bedload transport volume had decreased to 200,000 m³/year. (Rákóczi, 1989). As a result, after the 1970s, low and mean flow levels began to decrease due to incision of the Old Danube's riverbed. At the same time, the active floodplain continued to silt up with suspended sediments deposited during regular floods.

The ongoing industrial river dredging exacerbated these effects (Figure 29). The dredged gravel was used for concrete construction in the infrastructure and housing industries. The combined effect gradually made the level of the Danube riverbed significantly lower than the riverbed of the active floodplain branches. Therefore, the branches received less direct water supply from the main riverbed.

Due to the construction of stone embankments, the active floodplain branches received less and less flowing water at the upstream end, but the downstream ends were open. Hence, the water levels here corresponded to changes in the Old Danube's water level. Consequently, the upstream portion of the branch may dry up during low-flow periods, reducing the naturally flowing areas.

2.5. Gabčíkovo—Nagymaros Barrage Project

Due to regulations in the upper section of the Danube (Germany and Austria), both Hungary and Czechoslovakia aimed to improve navigation conditions, generate hydropower, enhance flood safety, and slow down riverbed erosion (Jakus et al., 2024).

After decades of planning, the two countries signed an international agreement in 1977 to implement the Gabčíkovo—Nagymaros Barrage Project (Hungary and Czechoslovakia, 1977).

Under the treaty, three major hydraulic structures were envisioned (Figure 30):

1. A barrage and lock at Dunakiliti (rkm 1842–1845) under Hungarian control, to divert flow into an artificial channel toward the hydropower complex.
2. The Gabčíkovo Hydropower Plant (HPP) (rkm 1860–1816) on the Czechoslovak side, fed by the diversion canal and insulated by dykes, with navigation locks built into the canal.
3. A downstream Nagymaros Barrage, ship lock, and power station (rkm 1696) designed to moderate water level fluctuations from the upstream scheme and support cross-border navigation

The Gabčíkovo Hydropower Plant was designed with eight Kaplan turbines, each with an installed capacity of 90 MW, for a total of 720 MW. The Nagymaros power station was designed with six identical, parallel-connected turbines—each with an output of 26.33 MW—for a total output of 158 MW (Eredeti tervek, Szigetkoz.biz). Planners also considered the floodplain branch system. They planned a 200 m³/s outlet structure next to the Dunakiliti barrage to release water from the reservoir into the side-branch network, which was designed to operate with the elevated water levels upstream of the barrage.

By the mid-1980s, however, the project became the subject of growing environmental and political controversy in Hungary. Concerns over ecological damage merged with broader public dissatisfaction under the single-party system, eroding trust in water management. On May 13, 1989, the Hungarian government suspended work on the Nagymaros barrage, while opposition movements pressed for democratic change. In response, Czechoslovakia prepared a fallback design, known as “Variant C,” to keep the Gabčíkovo HPP operational even without the Dunakiliti and Nagymaros structures.



Figure 30: a) Design Concepts and Plans: Photograph of a 3-dimensional raised relief map of the impacted area of the Gabčíkovo–Nagymaros Barrage Project; b) Axonometric computer drawing of Gabčíkovo HPP; c) Artistic representation of the Nagymaros Barrage

After Hungary's newly elected government notified Czechoslovakia in 1992 that it considered the 1977 Treaty terminated, Czechoslovakia implemented Variant C in October 1992, diverting most of the Danube's flow into the artificial canal. This unilateral action caused severe ecological impacts in Szigetköz. Following the dissolution of Czechoslovakia on January 1, 1993, Slovakia became the successor state involved in the dispute. Hungary and Slovakia jointly submitted the case to the International Court of Justice in 1993, and the Court delivered its judgment in 1997.

2.6. After 1992 – “C” variant

In 1992, Czechoslovakia implemented Variant C, diverting around 80% of the Danube's discharge into the artificial canal supplying the Gabčíkovo Hydropower Plant. The diversion was made possible by the Čunovo weir and the Gabčíkovo HPP, while the Dunakiliti barrage and the Szigetköz water-replenishment system were not completed and operated as originally planned (Figure 31).

The hydrological consequences were severe. Mean annual discharge in the Old Danube at Rajka fell from approximately 2,000 m³/s to 200–400 m³/s, representing a reduction of 80–90%. Water levels in the Old Danube consequently declined by approximately 3 m on average. In the most affected parts of Szigetköz, the lower river level locally reversed the former direction of groundwater flow. Instead of recharging the aquifer—the permeable gravel layer that stores and transmits groundwater—the Old Danube began to drain groundwater from the surrounding area. Average groundwater levels fell by approximately 1.5 m (Bárdossy and Molnár, 2004).

The effects were most immediate in Upper Szigetköz, where many branches in both the active and historical floodplains dried out. Because the water-replenishment system had not been completed, aquatic habitats lost important surface-water and groundwater inputs, and some water bodies disappeared entirely. The initial impacts recorded between 1992 and 1993 are illustrated in Figure 32.

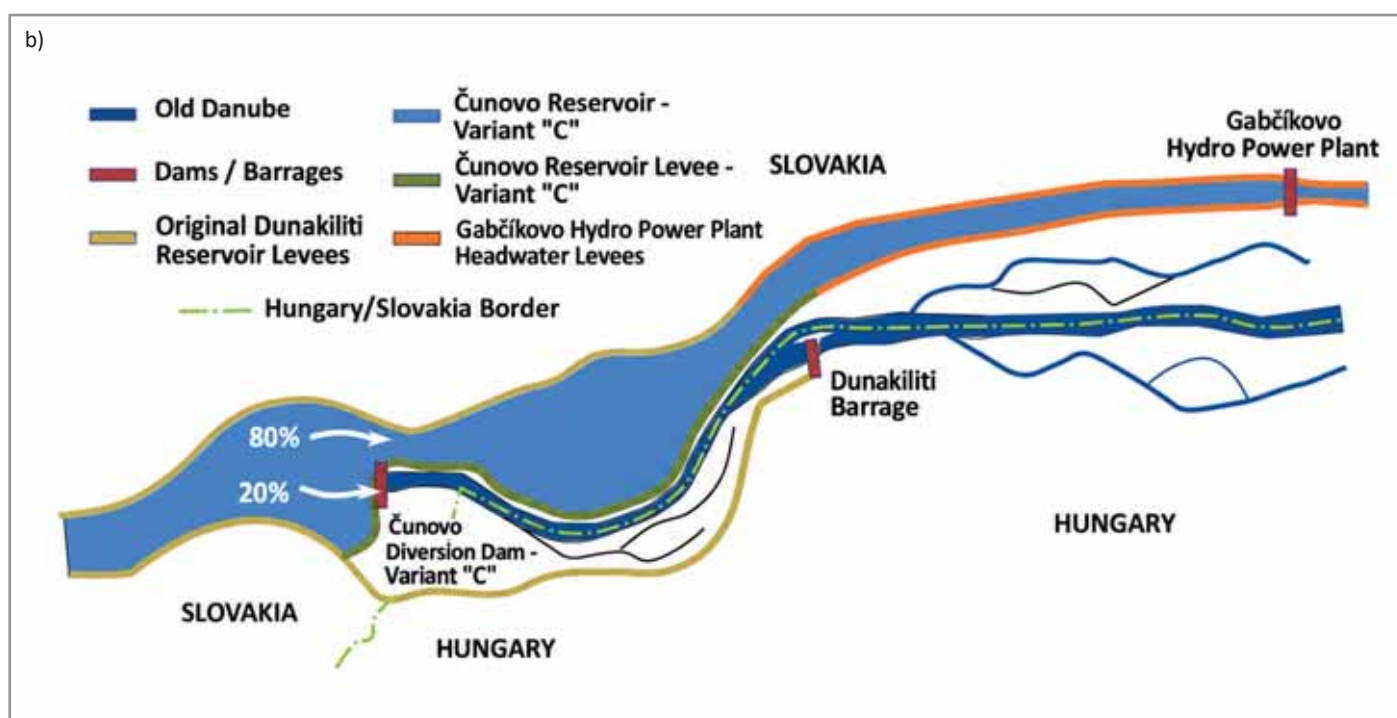


Figure 31: a), b) Variant "C"; c) – Čunovo Diversion Dam; d) Dunakiliti Barrage; e) Gabčíkovo HPP

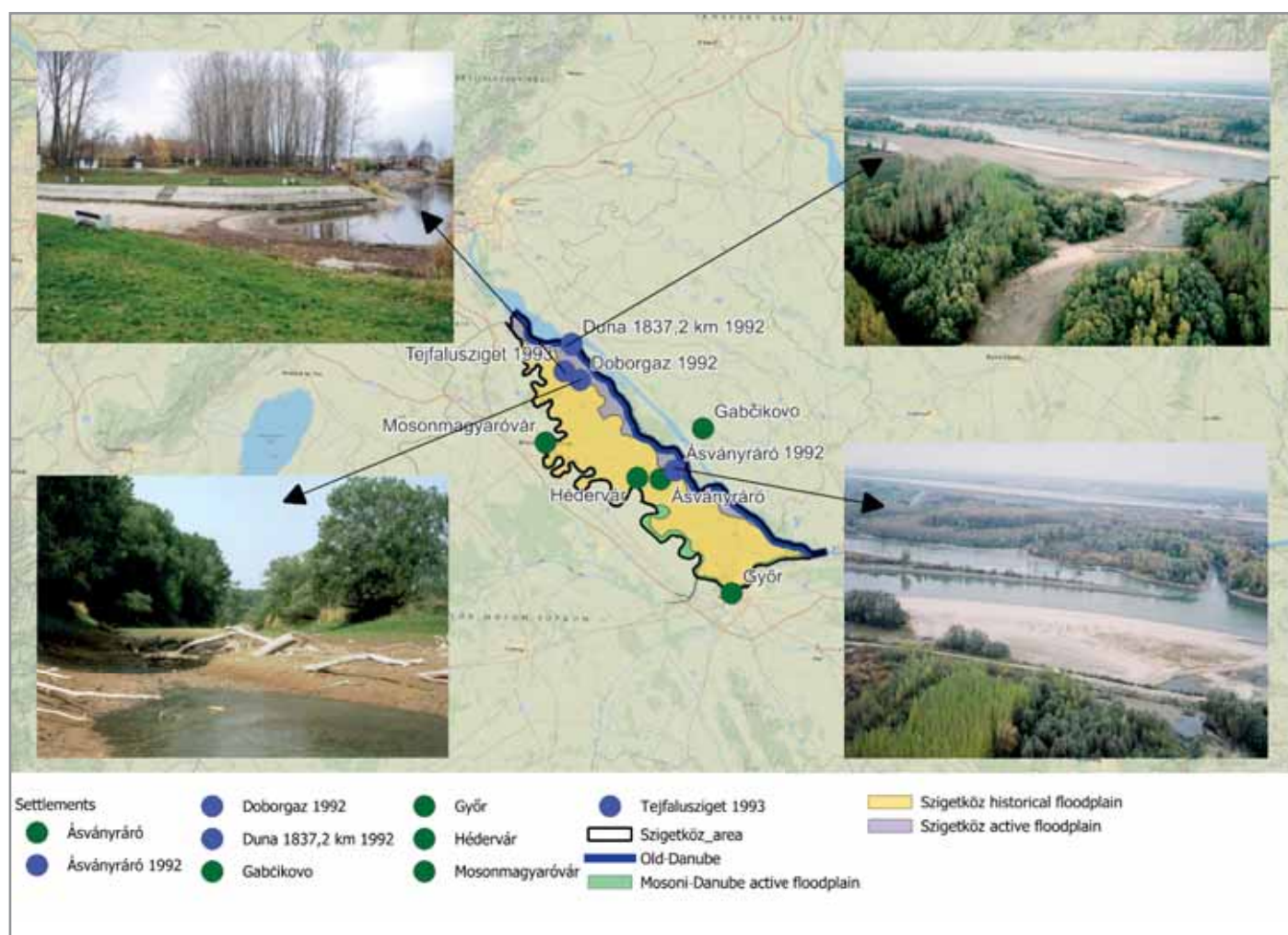


Figure 32: Hydrological impact of the Danube diversion in the Szigetköz between 1992 and 1993

Lower Szigetköz was initially less affected, but its condition subsequently deteriorated as progressive riverbed incision further reduced water levels and the supply of water to side branches.

The decline in surface-water and groundwater levels affected floodplain ecosystems, agriculture, and forestry (Kerekes, 1999). One beneficial effect was a more reliable water supply to the Mosoni-Danube, which had previously experienced shortages during low-flow periods. Under the modified operating regime, the Mosoni-Danube received a continuous discharge of approximately 20 m³/s from Čunovo, as envisaged in the Gabčíkovo–Nagymaros agreement.

2.7. Legal and environmental framework after 1992

Following the 1992 diversion, the management of Szigetköz was shaped by bilateral water-management arrangements, international adjudication, and European Union environmental legislation. These instruments have different legal and practical functions and should therefore be considered separately.

The 1994 Danube River Protection Convention established a broader transboundary framework for cooperation on the protection and sustainable use of the Danube, including water-quality protection, pollution control, monitoring, and coordinated river basin management (Danube River Protection Convention, 1994).

The 1995 bilateral agreement between Hungary and Slovakia established temporary arrangements for water distribution and provided a practical framework for testing and monitoring the Szigetköz water-replenishment system. Its technical provisions and implementation are discussed in Chapter 3.

In its judgment of September 25, 1997, the International Court of Justice found that both states had failed to comply with certain legal obligations. The Court required Hungary and Slovakia to negotiate in good faith, taking account of both the objectives of the 1977 Treaty and the factual situation that had developed. The judgment established a legal framework for further negotiations but did not prescribe the detailed hydraulic or ecological operation of the river system (International Court of Justice, 1997).

The EU Water Framework Directive introduced a separate environmental framework for the management of surface waters and groundwater. Water bodies whose physical characteristics have been substantially altered for uses such as flood protection, navigation, water supply, or energy production may be designated as heavily modified where the relevant legal conditions are met. For such water bodies, the environmental objective is good ecological potential and good chemical status rather than the complete recreation of an assumed undisturbed condition (European Parliament and Council, 2000).

The Natura 2000 framework, based on the Habitats Directive and the Birds Directive, adds site-, habitat-, and species-specific conservation requirements. Water management in Szigetköz must therefore support the maintenance or restoration of the favorable conservation status of the habitats and species for which the sites were designated. These objectives may depend on water quality, water levels, seasonal inundation, habitat connectivity, and the timing and duration of hydrological events (Council of the European Communities, 1992; European Parliament and Council, 2009).

Regulation (EU) 2024/1991 on nature restoration provides an additional framework for restoring freshwater ecosystems, river connectivity, and associated floodplain functions. The regulation requires restoration planning to consider artificial barriers and measures that improve the natural functions of rivers and floodplains while also accounting for the justified socioeconomic functions of existing infrastructure (European Parliament and Council, 2024).

Fish passages support longitudinal connectivity by allowing fish and other aquatic organisms to move along a river or branch system past individual barriers. Floodplain rehabilitation addresses a wider range of processes, including lateral connections between the main river and its side branches, periodic inundation, spawning and nursery habitats, sediment and nutrient exchange, and interactions between surface water and groundwater. Fish passage is therefore an important component of rehabilitation, but it cannot by itself restore the full hydrological and ecological functioning of a floodplain (European Parliament and Council, 2024).

2.8. Summary: Historical transformations and their legacy

The historical development of Szigetköz can be divided into five principal phases:

Phase 1 — The natural floodplain and early navigation measures

1. Dynamic Floodplain before Large-Scale Regulation (18th century):
The Szigetköz reach functioned as a dynamic braided river system with numerous free-flowing branches. Frequent floods shaped both the riverbed and the surrounding floodplain.
2. Initial Interventions (17th–18th centuries):
Towpaths were built to support shipping despite frequent changes in the river's course.

Phase 2 — River regulation, flood protection, and drainage

3. 19th-Century River Regulation:
Large-scale works stabilized the Old Danube as the main channel and laid the foundation for the separation of the active and historical floodplains.
4. Floodgate Construction (1905–1908):
The Rajka floodgate regulated water entering the Mosoni-Danube and significantly altered the area's hydro-morphology.
5. Levee System Expansion (late 19th–early 20th century):
Extended levees reduced regular flooding but contributed to sediment accumulation, higher flood levels, and increased seepage.
6. Drainage Canals (early 20th century):
Canals and pumping stations were constructed to manage excess water on the historical floodplain, often using former oxbows and side branches.

Phase 3 — Reduced connectivity and changing sediment conditions

7. Natural Connections Persisted (until the 1950s):
Floodplain branches still received water dynamically during floods, although sediment accumulation increasingly obstructed navigation.
8. Mid-20th-Century Alterations:
Groins, branch-control structures, and dredging improved navigation but reduced dynamic flow in many side branches.
9. Bedload Reduction and Riverbed Incision (1960s–1990s):
Upstream dams in Austria and Germany reduced coarse-sediment transport, contributing to riverbed incision and altered hydrological conditions.

Phase 4 — The barrage project and the 1992 diversion**10. Gabčíkovo–Nagymaros Barrage Project (1977):**

Hungary and Czechoslovakia agreed to construct a hydropower and navigation system at Dunakiliti, Gabčíkovo, and Nagymaros, including measures to replenish the Szigetköz floodplain.

11. Public Opposition (1980s):

Environmental concerns and public protests in Hungary led to the suspension of the Nagymaros barrage in 1989.

12. Implementation of Variant C (1992):

After Hungary declared the 1977 Treaty terminated, Czechoslovakia implemented Variant C and diverted approximately 80% of the Danube's flow into the new canal system.

- Old Danube: Discharge at Rajka fell from approximately 2,000 m³/s to 200–400 m³/s, and water levels declined by about 3 meters.
- Groundwater: The water table declined by approximately 1.5 meters in the most affected areas.
- Floodplain branches: Many branches in Upper Szigetköz dried out or became disconnected.
- Lower Szigetköz: Conditions deteriorated more gradually as riverbed incision continued.
- Land use: Lower groundwater and soil moisture affected agriculture and forestry.
- Mosoni-Danube: A continuous discharge of approximately 20 m³/s improved low-flow water supply.

Figure 33 summarizes the sequence of major river and floodplain transformations and their principal consequences.

The history of Szigetköz demonstrates that present conditions cannot be attributed to a single intervention. Long-term river regulation, floodplain separation, sediment imbalance, dredging, and the 1992 diversion produced cumulative and interacting effects. The diversion was the most abrupt and severe change, but the floodplain's vulnerability had already increased during the preceding period of regulation. Rehabilitation objectives must therefore respond to the combined legacy of these transformations rather than attempt to recreate an undefined pristine state.

Phase 5 — Damage mitigation and long-term rehabilitation**13. Initial Water Replenishment and Bilateral Arrangements (1993–1995):**

Hungary implemented emergency measures and began developing the Szigetköz water-replenishment system. Hungary and Slovakia also established arrangements for water distribution, test operation, and joint monitoring.

14. Judgment of the International Court of Justice (1997):

The Court found that both states had failed to comply with certain legal obligations and required them to negotiate in good faith, taking into account the objectives of the 1977 Treaty and the situation that had developed.

15. Long-Term Development of the Water-Replenishment System (1995–2023):

Hungary progressively expanded the system through additional inlets, outlets, control structures, fish passages, monitoring, operating regulations, and later rehabilitation measures. The system now supplies controlled flows to parts of the active and historical floodplains and has improved water levels and ecological conditions.

CHANGES OF THE SZIGETKÖZ DANUBE AND THEIR IMPACTS

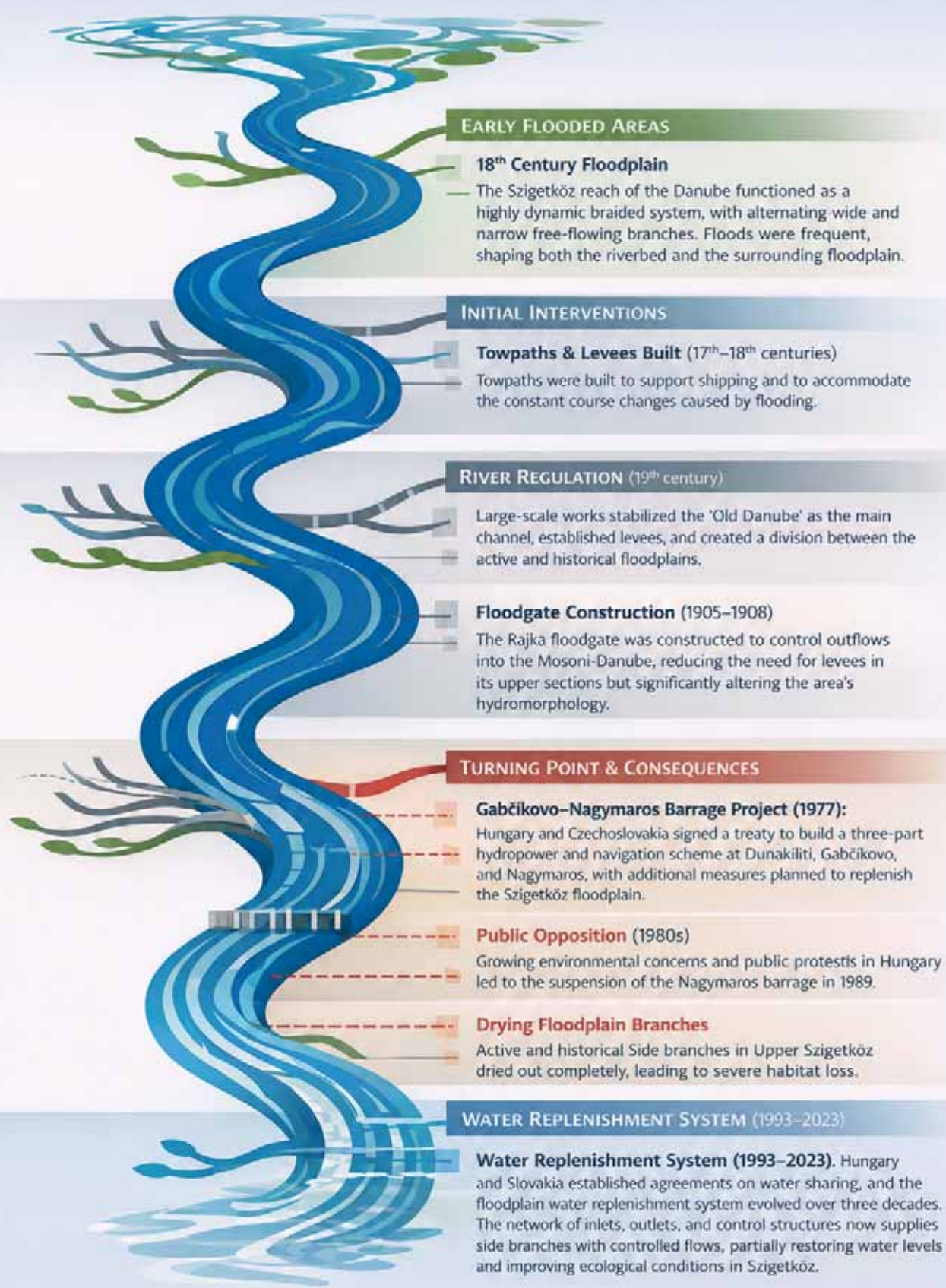


Figure 33: Summary of the Szigetköz Danube Changes and Their Impacts

The Concrete Ship of Ásványráró – A Story Beneath the Water

A few tons of history lie beneath the surface of the Bagaméri branch, just below the Árvai closure. The remains of a 30-meter-long reinforced concrete ship rest underwater, marked only by a single visible post. Built around the time of the Second World War, likely due to steel shortages, the vessel once served transport purposes before becoming a familiar feature of the local landscape. Over time, it turned into a playground for children and a place of shared memories. After a storm sank it, the ship was left in place, and since the 2016 rehabilitation, only a small trace indicates its presence beneath the water.

Around this submerged structure, numerous stories and legends began to form. One of the most enduring tells of its origins during the final years of the war, when a group of engineers was tasked with building a vessel capable of withstanding extreme conditions. According to local imagination, the ship not only served its practical purpose but also gained a special reputation: it was said to protect its cargo and guide those who traveled upon it safely home. Another story recalls a stormy night decades later, when fishermen sought shelter on the abandoned vessel. Among them was an old river sailor who warned that the ship would remain afloat only for those who approached it with honest intentions. As the story goes, a merchant driven by greed attempted to hide valuables aboard the ship. At that moment, the vessel trembled and slowly sank beneath the water, as if responding to the intentions of those on board.

Today, the concrete ship rests on the riverbed, its presence marked only by a single visible remnant above the water. It remains both a historical relic and a source of local stories, where memory and imagination meet. Standing nearby or passing over it by canoe, visitors can still sense the quiet legacy of the “concrete ship” beneath the surface.



3. IMPLEMENTED MEASURES

This chapter focuses on the emergency and early-phase water replenishment measures implemented in Szigetköz between 1992 and 1995 following the diversion of the Danube. It describes the immediate technical interventions, stakeholder-driven objective setting, and the Hungarian–Slovak interim agreement, which together stabilized water levels and laid the foundation for later floodplain restoration.



Figure 34: The upstream reach of the Mosoni-Danube at the Mosonmagyaróvár barrage.



Transferable lesson 3 — Agree on objectives before finalising the design

Challenge addressed

Emergency measures can reduce immediate damage, but long-term floodplain rehabilitation must balance ecological requirements, flood protection, water supply, agriculture, forestry, fisheries, recreation, and local interests.

Approach used in Szigetköz

An open planning process identified the main stakeholder groups, negotiated priorities, and defined a shared reference period and ecological requirements. These objectives were then translated into a dynamic water-replenishment system for the active floodplain, historical floodplain, and Mosoni-Danube. Early visible improvements also helped build public trust and support for further measures.

General principle

Agree on objectives, priorities, and constraints before selecting structures and operating rules.

Evidence and operational relevance

Application elsewhere requires representative stakeholder participation, neutral facilitation, a shared information base, clearly stated technical and ecological constraints, and an institutional process for approving agreements.

Conditions for transfer

Application elsewhere requires historical maps, hydrological and engineering records, land-use and ecological information, and local knowledge. Immediate impacts should be distinguished from longer-term changes in channels, groundwater, habitats, and land use. Stakeholder involvement is also a prerequisite.

Suggested indicators

Stakeholder groups represented; objectives formally agreed; conflicts identified and resolved; reference conditions defined; ecological and water-use requirements translated into design parameters; and operating flexibility retained.

Implemented measures

The diversion of the Danube fundamentally altered the hydrological conditions of Szigetköz by disrupting the connections between the main river, the floodplain branch systems, and groundwater. Water levels declined, flow patterns changed, and large parts of the side-channel networks became hydraulically disconnected. These changes affected ecological processes, water availability, and land use throughout the region. Addressing these impacts required both immediate intervention and long-term planning. Between 1992 and 2022, a series of measures was implemented to improve water levels in the Mosoni-Danube and to re-establish more dynamic flow conditions in the active and historical floodplain branch systems. The measures combined technical solutions with increasing attention to ecological connectivity, adjustable sys-

tem operation, and adaptive management. Stakeholder engagement and negotiation also became essential because water-management decisions directly affected local communities, agriculture, economic activities, and nature-conservation objectives. This chapter describes the initial response between 1992 and 1995: the emergency measures, the open planning process, the definition of shared objectives, the Hungarian–Slovak interim agreement, and the design and construction of the core water-replenishment system. The later test operation, operating rules, institutional arrangements, and extensions of the rehabilitation are presented in Chapters 4–8.

The table below summarizes the implemented measures across the different domains of the Szigetköz floodplain following the diversion of the Danube.

	Active floodplain	Historical floodplain	Mosoni-Danube
1992–1993 Immediate measures	Downstream branch closing	A connection channel to the toe drain was built	20 m ³ /s supply
Until 1995 Open planning	Dynamic water replenishment design		
1995 Agreement between Hungary and Slovakia on water sharing	• Temporary water-sharing agreement • Construction of the submerged weir in the Old Danube riverbed • Joint monitoring activities		
1995	Submerged weir Dunakiliti operation Design and construction of water-retaining structures Dynamic replenishment design	Dynamic replenishment design Upper Szigetköz floodplain drainage system capacity increased and improved	Dynamic replenishment design
1995–2000 Test operation	Monitoring system	Monitoring system	Monitoring system
2000 Operating permit	As-built structures Operating regulations	As-built structures Operating regulations	Operating regulations
2001	Szigetköz operating committee		
2015	Lower Szigetköz floodplain rehabilitation	Lower Szigetköz floodplain rehabilitation	Longitudinal and lateral connectivity with hydraulic structures
2022			Mosoni-Danube outflow structure in operation

3.1. Immediate actions (1992–1993)

Following the diversion of the Danube in October 1992, the immediate priority was to prevent further drying and restore a basic water supply to the branch systems. Water levels and groundwater declined rapidly, while many channels and water-dependent habitats became disconnected from the river. The first measures were implemented under severe time and infrastructure constraints. They aimed to maintain a continuous supply to the Mosoni-Danube and to introduce a limited but controllable flow into the active and historical floodplain branches. Although these interventions reduced some of the immediate damage, their limited capacity demonstrated the need for a coordinated, system-wide solution. The upstream reach of the Mosoni-Danube at the Mosonmagyaróvár Barrage is shown in Figure 34.

3.1.1. Water Replenishment of the Historical Floodplain

Conditions before and during the construction of the Gabčíkovo HPP:

Because the flood-protection levee had long severed direct surface connections to the Danube, the historical floodplain gradually became a landscape separated from the river that had once shaped it. Instead of regular flooding, it relied mainly on groundwater and a drainage network that carried excess water into the Mosoni-Danube during high flows. As water levels in the Danube declined gradually in the second half of the 20th century, the hydraulic connection between the Danube and the groundwater system weakened. Groundwater levels dropped, small canals lost their flow, and wetlands that had once been persistent features of the landscape began to dry out during low-water periods. Areas that had depended on seasonal water presence became increasingly disconnected from natural processes. In response, the drainage system was later adapted for dual use, allowing it not only to remove excess water but also to supply it when needed (Tatai and Pap, 2023).

Immediate measures after the diversion:

Drying accelerated after the 1992 diversion, particularly in the Upper and Middle Szigetköz. At that time, approximately 200 m³/s continued to flow into the Old Danube, while around 20 m³/s was supplied through a channel connected to the toe-drain system before reaching the Mosoni-Danube. The main flow routes are shown in Figure 35, while Figure 36 shows the supply channel and toe-drain system at the Rajka sluice gate. Local water-management experts proposed using this existing infrastructure to reconnect the toe-drain channel with the historical floodplain branch system. The location and construction of this emergency connection are shown in Figure 37,

while Figure 41 provides a closer view of the connection between the toe-drain channel and the Zátonyi Danube. The new connection allowed a few cubic meters of water per second to enter channels that passed near several settlements.

The government authority approved the plan as an emergency measure, allowing rapid implementation under an emergency procedure. Approximately six months after the diversion, water began to return to sections of the Upper Szigetköz historical floodplain, including the Zátonyi Danube. The contrast between the dry conditions in November 1992 and the return of water by May 1993 can be seen in Figures 38 and 39. With the help of sluice gates, water levels could be partially controlled, and formerly dry channels began to refill. Figure 42 shows the replenished Zátonyi Danube within the historical floodplain system. The change was immediately visible, especially near residential areas. The return of water not only improved local conditions but also gave residents greater confidence that the damage could be reduced.

3.1.2. Emergency measures in the active floodplain

The drying of the active floodplain following the diversion is illustrated in Figure 40. Emergency measures on the active floodplain included temporary water supply solutions such as diesel-powered pumping from the remaining Danube flow, as well as localized interventions to distribute water into side branches. In some areas, these measures provided short-term relief by rewetting previously dried sections and supporting limited ecological functions. However, the effectiveness of these interventions varied significantly across the floodplain. Diesel-powered pumping, in particular, proved unreliable, costly, and insufficient for maintaining stable, continuous water levels. Overall, these experiences demonstrated that while emergency actions could offer temporary benefits, sustainable water management of the active floodplain required more complex, regulated hydraulic systems.

Following the diversion of the Danube in the Szigetköz region, many residents were skeptical that the water would ever return to flow behind their homes. Consequently, sections of the former riverbed were used as temporary storage areas, for instance, to stockpile animal feed harvested in autumn. When water was eventually reintroduced, some of these feed piles were partially flooded and washed away. Despite this, the overall response was positive, with most people welcoming the return of the water. Only a few farmers felt regret, having not taken the prior warnings from the water management authorities seriously.

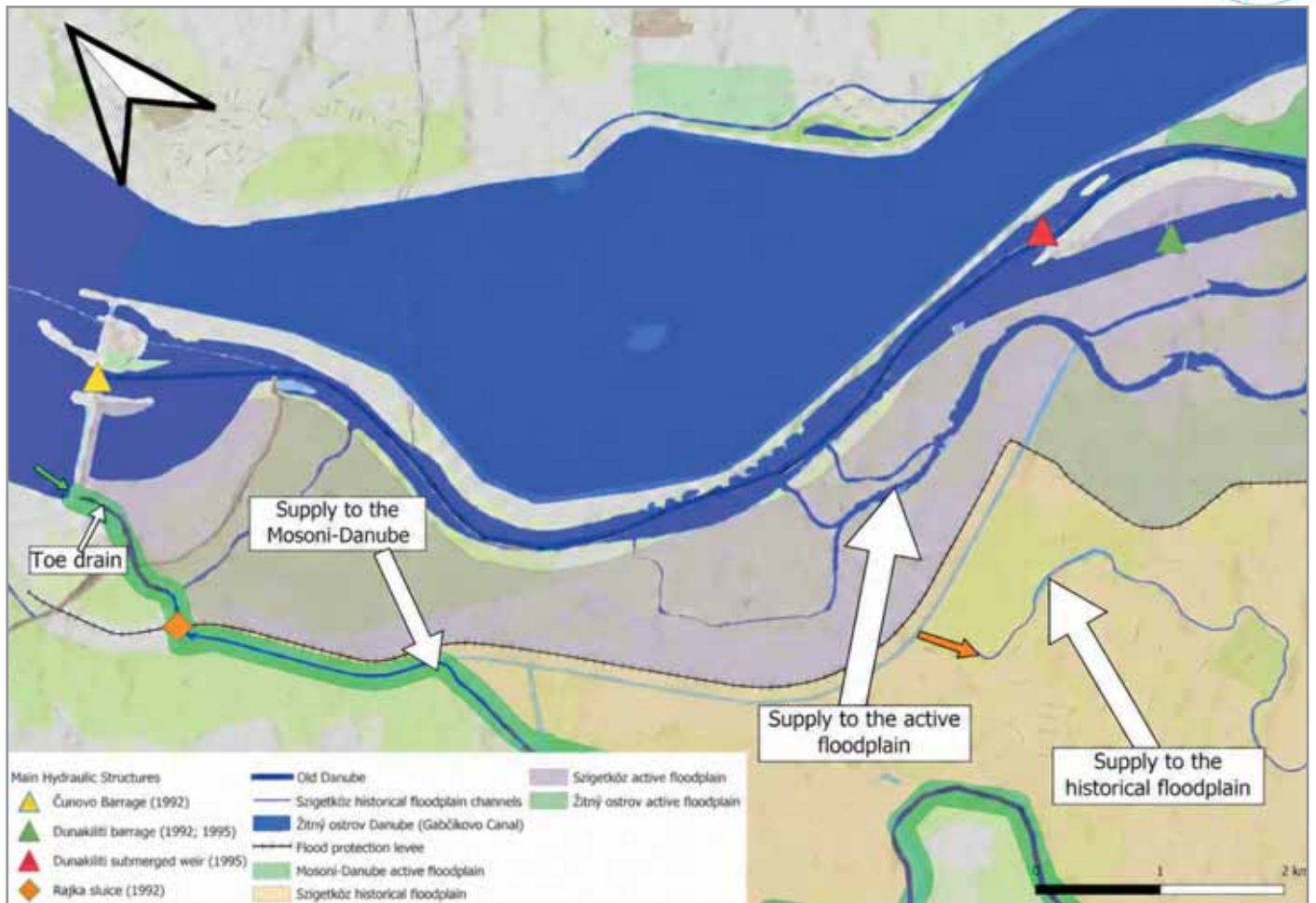


Figure 35: Flows in the supply channel and toe drain towards the Mosoni-Danube



Figure 36: Flow in the supply channel and toe drain at the Rajka sluice gate

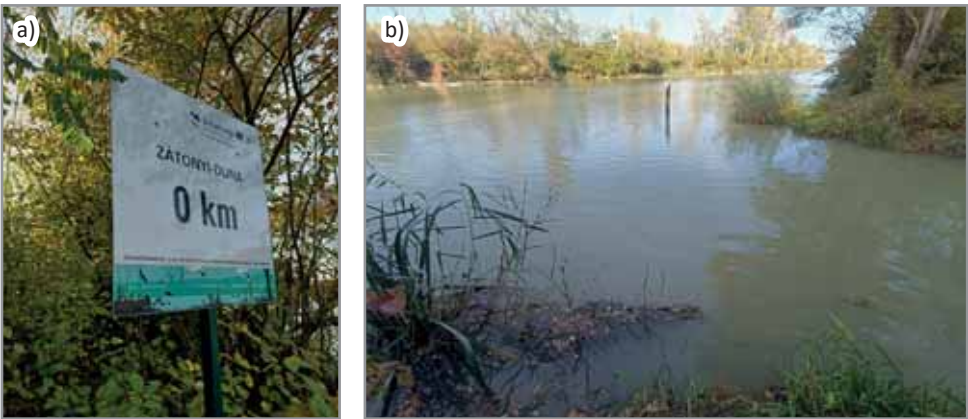


Figure 37: a) Starting point of the Historical floodplain branch system; b) The connection between the toe-drain and the historical floodplain branch system was established as an emergency measure during 1993



Figure 38: Dry conditions in the Zátónyi-Danube near Doborgazsziget in November 1992.



Figure 39: The Zátónyi-Danube near Doborgazsziget after the return of water in May 1993.



Figure 40: Dry active floodplain branches following the diversion of the Danube. Source: Fertő–Hanság National Park Directorate.



Figure 41: Connection between the toe-drain channel and the Zátónyi-Danube



Figure 42: The replenished Zátónyi-Danube in the historical floodplain water-replenishment system.

3.1.3. Implication of the emergency measures

The comparison in Figures 38 and 39 shows that relatively simple interventions can quickly restore water to individual dry channels. They also showed that pumping and isolated structures could not provide stable conditions across the entire floodplain. A long-term response required an integrated and adjustable water-replenishment system, designed for low-maintenance operation and gravity-driven conveyance wherever possible. Its objectives and operating priorities also had to be agreed with the communities, authorities, economic users, and conservation organizations affected by water management decisions.

3.2. Stakeholder involvement in defining the main objectives

To reduce the damage and establish a workable framework for the water-replenishment system, clear objectives had to be agreed through negotiation. This required coordination not only between Hungary and Slovakia but also among stakeholders within Hungary, who held different views on the future of the floodplain. The visible success of the emergency replenishment in the historical floodplain showed residents that practical improvements were possible. This increased public confidence and encouraged greater cooperation with water-management authorities in developing a long-term solution.

Open planning and stakeholder mapping

The county government office initiated an open planning process and carried it out under the supervision of the North-Transdanubian Water Directorate. The first step was to identify the main groups affected by the decisions. These included local governments, regional economic actors, and civil organizations involved in environmental protection and community development.

A neutral expert team supported the process. Its members did not represent individual stakeholder interests. Instead, they guided the discussions, helped manage conflicts, and ensured that technical experts participated as impartial advisers rather than as parties seeking to promote their own preferred solutions. The neutral facilitation process allowed stakeholders to present their concerns, understand others' views, and compare possible solutions in an organized way.

Negotiating priorities

The first meetings revealed widely differing expectations. Some environmental organizations initially supported extensive renaturalization, including the removal of hydraulic structures and even flood-protection levees. Farmers and foresters, by contrast, emphasized the protection of cultivated land and the maintenance of suitable ground-

water conditions. To systematically compare the many proposals, the planning team applied value analysis, a structured method for examining needs, functions, priorities, and feasible solutions (SAVE, 2015). The process established the following order of priorities:

1. Flood protection
2. Drinking water supply
3. Nature conservation
4. Fishing
5. Forestry
6. Tourism

Navigation was excluded, as international shipping had already been rerouted through the Gabčíkovo supply channel. Flood protection remained the only non-negotiable item: all groups accepted that levees must remain in place and, if possible, their protective function should be enhanced. Once this principle was agreed, attention could focus on ecological restoration and other interests.

Determination of target conditions

With the main priorities clarified, experts and stakeholders agreed that the water-replenishment system should improve aquatic habitats while continuing to protect settlements, agricultural land, and drinking-water resources. The Dunakiliti barrage had originally been constructed as part of the Gabčíkovo–Nagymaros Project. After the Čunovo structure assumed the upstream control role originally planned for Dunakiliti, the available facilities at Dunakiliti were brought into use as part of the Hungarian water-replenishment system. This provided a technical basis for distributing water dynamically rather than maintaining a single fixed water level. Three guiding principles were agreed:

1. Select a reference period during which the active floodplain branch system still maintained a continuous connection with the Danube.
2. Reproduce changing water levels and flows rather than maintain static conditions.
3. Avoid excessively long water residence times in the branches in order to limit eutrophication.

These principles translated broad stakeholder expectations into practical objectives that could guide the system's technical design.

Significance

The open planning process shaped more than the technical design. It also provided a way to identify conflicts, define shared boundaries, and develop compromises among ecological, economic, and social interests. Stakeholder participation strengthened public acceptance of the proposed measures and laid the foundation for continued involvement in the system's later operation. The selection of a reference period, open planning, stakeholder involvement, social oversight, and the use of value analysis are among the most transferable elements of the Szigetköz experience.

3.3. Planning the water replenishment systems

Beyond the main objectives agreed during the open planning process, the design also had to consider local needs. Municipalities sought to support water-based tourism, nature conservation organizations sought to limit access to sensitive habitats, and forestry required access to forest stands for timber management. These interests did not always require the same water levels or operating conditions. To support informed decisions, the expert team collected, processed, and presented the available evidence to stakeholders. Most of the information consisted of long-term water-level and discharge records, while systematic water-quality and hydrobiological data were available mainly from the 1950s onwards. The planning process therefore combined measured data, historical information, ecological knowledge, and the experience of local stakeholders.

3.3.1. Finding a reference period

The first task was to identify a reference period that could guide the ecological and hydrological objectives of the active floodplain. The intention was not to recreate an untouched floodplain, because major regulation and flood-protection works had already transformed Szigetköz. Instead, the planners sought a well-documented period when the active floodplain branches were still strongly and continuously influenced by the natural flow variations of the Danube.

Continuous hydrological records have been available from Dunaremete, in the central part of Szigetköz, since 1901. For earlier periods, the evidence was limited mainly to maps and individual measurements. After reviewing available hydrological and water-quality information, the planning team also considered recollections from older stakeholders, who identified the 1950s as a period when water conditions and the ecological character of the floodplain were still considered favorable. Their recollections supplemented the measured records and historical information but did not replace them. The historical review helped explain why this period was appropriate. During the 1960s, further river-regulation works were introduced primarily to improve navigation. Control structures were constructed at connections between the main channel and the side branches to retain water in the Old Danube during low and medium flows. Water could enter many branches only when higher river levels overtopped these structures. The construction of control structures at the entrances to the side branches reduced the frequency of connection with the Old Danube and weakened the natural variability of the branch system. Stakeholders therefore selected 1950–1959 as the practical planning period. The objective was

to reproduce the characteristic water levels, flow relationships, and variability of that period as far as technically possible, rather than to copy every historical condition exactly. The selection of a documented and achievable reference period was one of the most transferable elements of the Szigetköz planning process.

The hydrological analysis used two observation stations. Bratislava (Dévény), upstream of the direct influence of the Gabčíkovo structures, provided a reference for Danube discharge. Dunaremete represented water-level conditions within Szigetköz. Comparing the long-term records from the two stations enabled separating changes in the river's incoming discharge from those occurring within the Szigetköz reach. The discharge records at Bratislava showed no comparable long-term shift in low and mean flows. At Dunaremete, however, the relationship between Danube discharge and local water level changed over time, indicating adjustments in channel form and hydraulic conditions. These contrasting trends are shown in Figure 43.

To examine this change more closely, rating curves—the relationships between discharge at Bratislava and water level at Dunaremete—were prepared for two periods: 1950–1959 and 1989–1992. During the later period, water levels at Dunaremete were lower under low-flow conditions but higher at large discharges than during the reference period, as shown in Figure 44. This result demonstrated that the channel no longer responded to Danube discharge in the same way as it had during the 1950s.

The analysis supported the use of the 1950s as the reference period for the active floodplain. During that decade, the branch system retained a stronger connection with the Danube, and the Mosoni-Danube received a continuous supply through the Rajka floodgate that broadly followed the river's natural variations. The historical floodplain required a different approach. By the 1950s, it had already been separated from regular Danube flooding by the flood-protection levees and depended mainly on groundwater, drainage channels, and controlled water supply. Its target conditions could therefore not be defined simply by copying those of the active floodplain.

3.3.2. Ensuring dynamic water level changes in replenished waterbodies

A central design principle was that the replenishment system should reproduce changing water conditions rather than maintain one fixed level. Water-level fluctuations are important because they influence connections between channels, the extent of shallow-water habitats, groundwater recharge, sediment movement, and the availability of feeding and spawning areas.

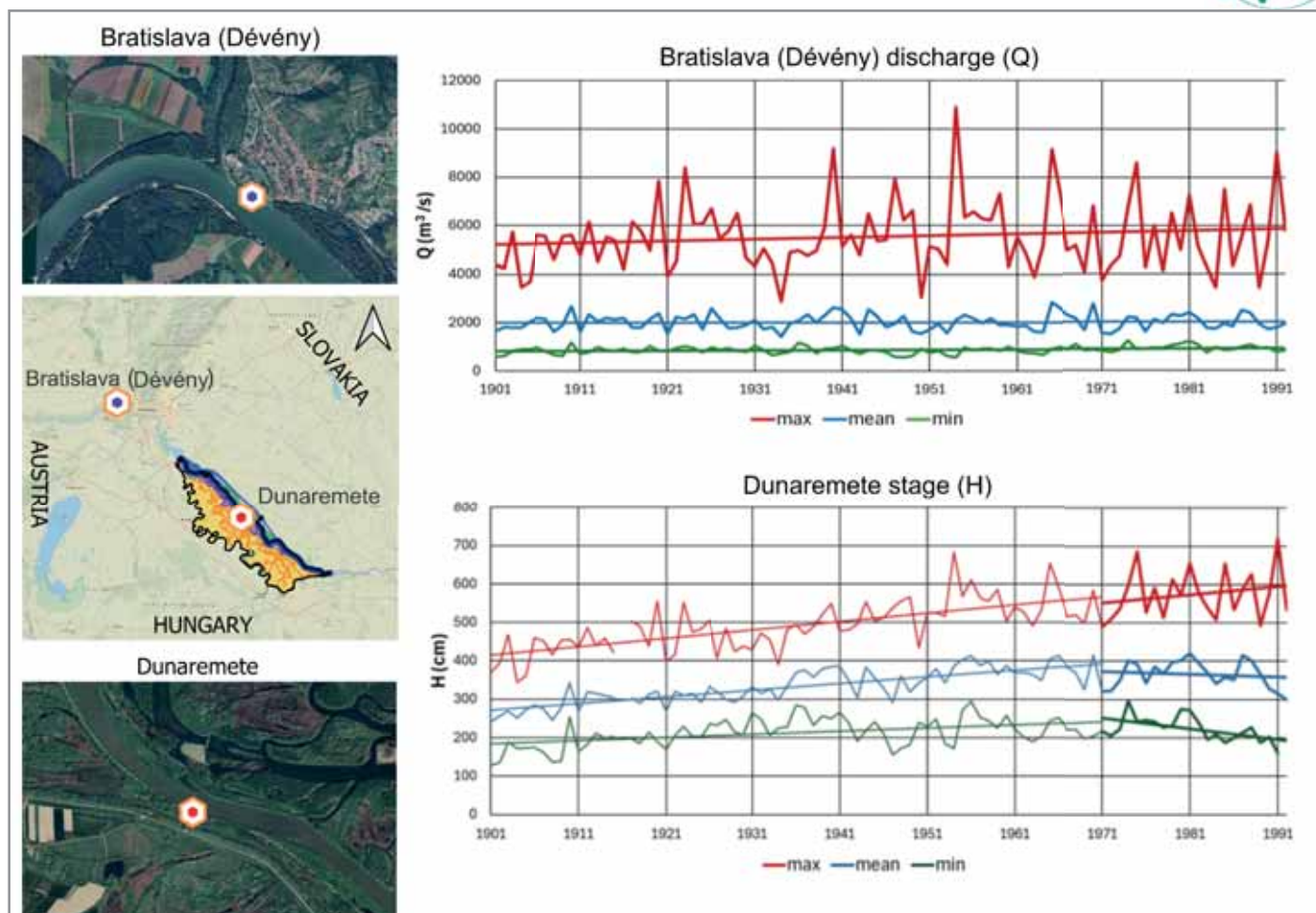


Figure 43: Flow trends in Dunaremete (stage) and Bratislava (Dévény) (discharge).

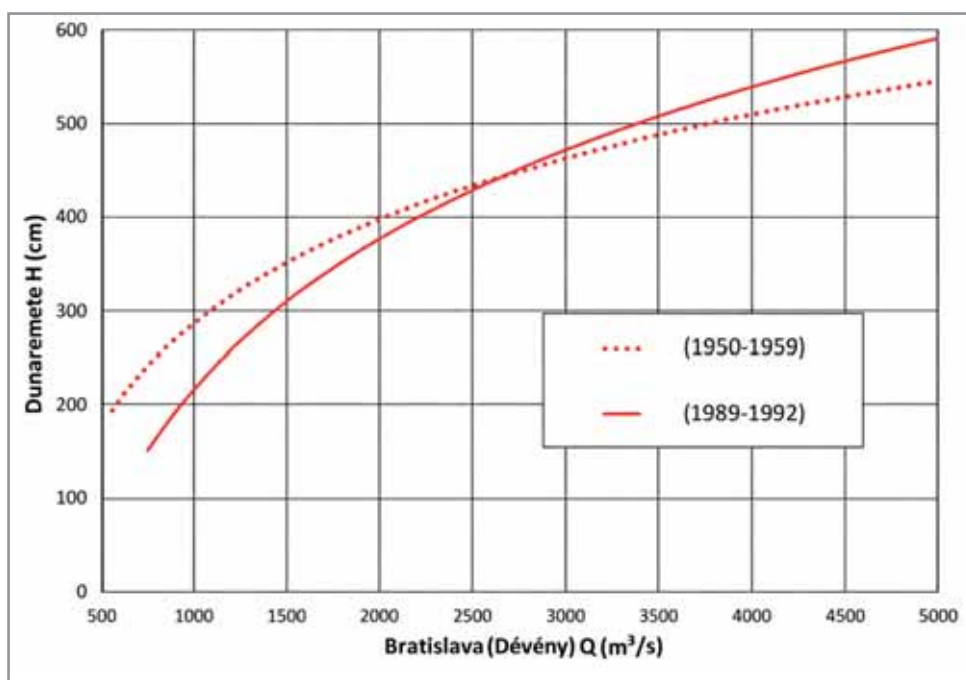


Figure 44: Rating curve based on Danube discharge at Bratislava (Dévény) and the corresponding river stage at Dunaremete during 1950–1959 and 1989–1992.

To define the timing and scale of these changes, daily and monthly low, mean, and high water levels were analyzed. Records from Dunaremete showed that daily water levels during the 1950–1959 reference period commonly fluctuated by 100–200 cm, with larger changes occurring during some events. The pattern varied between seasons and from year to year, but did not follow a single uniform annual course (Figure 45).

Monthly values showed a smoother seasonal pattern. Water levels were generally lower in winter, while the highest monthly low and mean values usually occurred in May, June, and July. High-water events followed a somewhat different pattern. Monthly averages, however, could be strongly affected by a small number of extreme days and concealed many of the shorter changes that shaped floodplain habitats (Figure 46).

The analysis therefore showed that monthly averages alone could not adequately represent the natural variability of the Danube. At the planning stage, stakeholders accepted daily tracking of river conditions as the basis for

dynamic operation. The decision to base system operation on daily river conditions marked an important departure from conventional management based on fixed or seasonal target levels. The initial daily approach was later refined during test operation in response to practical experience and erosion risks.

3.3.3. Ecological requirements

Reproducing water-level changes was only one part of the design. The system also had to maintain adequate water exchange and prevent water-quality problems. Water residence time—the period for which water remains within a branch before being renewed—and flow velocity were therefore treated as ecological design parameters. The objective was not to maximize flow throughout every branch. A healthy floodplain contains a varied mosaic of flowing channels, slow-flowing areas, backwaters, and temporarily connected habitats. At the same time, prolonged stagnation had to be avoided, as it could lead to excessive algal growth, oxygen depletion, and sediment accumulation.

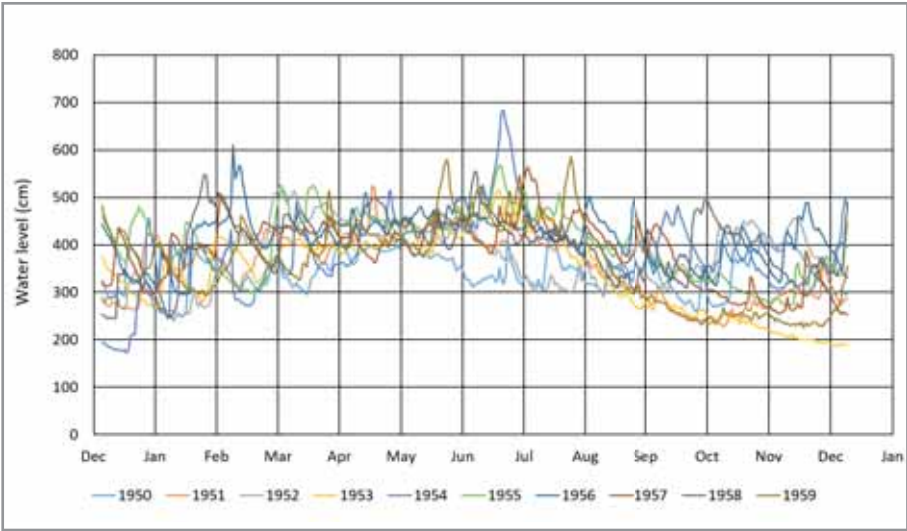


Figure 45: Changes in daily water levels between 1950 and 1959 in Dunaremete

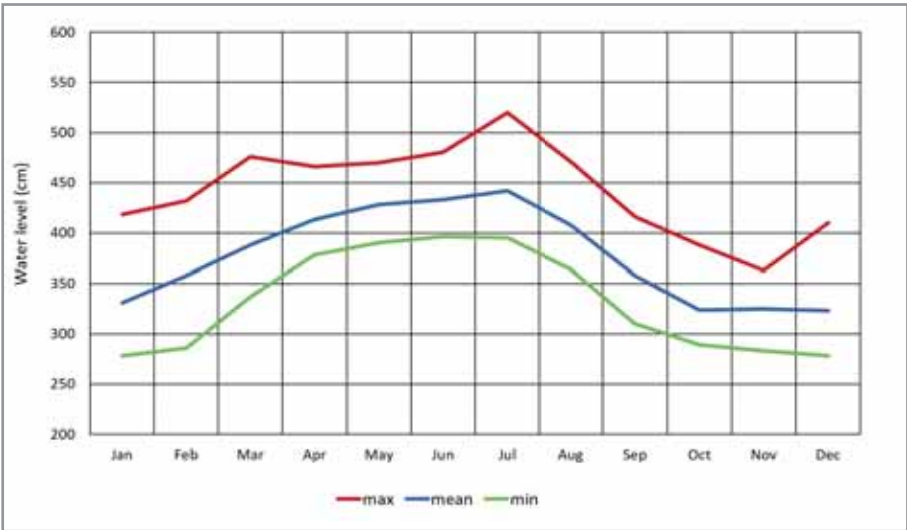


Figure 46: Monthly minimum, mean, and maximum water levels at Dunaremete during 1950–1959

Previous hydrobiological assessments indicated that the risk of eutrophication increased when water remained in the branch system for more than approximately four days (Pannonhalmi, 1999). The planning process therefore adopted four days as an approximate maximum residence time. This limit was intended to reduce eutrophication while preserving the diverse mosaic of floodplain habitats. A minimum cross-sectional average flow velocity of 0.3 m/s was also applied in the main branches to reduce sediment deposition and channel blockage. To determine the discharge required to meet these conditions, a detailed survey of the branch system was conducted, with cross-sections measured at approximately 200 m intervals. The survey data were then used in a hydrodynamic model—a computer-based representation of how water moves through the channel network. The modeling indicated that a discharge of approximately 40–50 m³/s was needed to keep residence times below four days and average flow velocities at or above 0.3 m/s. In the main replenishment branch, a discharge of approximately 120–150 m³/s was required to achieve water levels comparable with those recorded during average-flow conditions in the 1950s reference period (Pannonhalmi, 1999). The following design criteria were established:

- use the characteristic water levels and dynamics of the 1950s as the reference for the active floodplain, while considering the related groundwater response;
- adjust water supply dynamically in response to changing Danube conditions;
- maintain average flow velocities above 0.3 m/s in the main branches;
- keep water residence time below approximately four days;
- provide approximately 40–150 m³/s to the active floodplain branch system, depending on low- or average-flow conditions.

Together, these criteria translated broad ecological and stakeholder objectives into measurable requirements for system design and operation. Once the required flows and water levels had been defined, an international agreement on the amount of water available to Szigetköz became both possible and necessary.

3.4. Interim Agreement between the Governments of Hungary and the Slovak Republic

By the mid-1990s, the ecological and hydrological objectives defined for Szigetköz could not be achieved without cooperation between Hungary and Slovakia. The average discharge remaining in the Old Danube, approximately 200–250 m³/s, was insufficient to support the intended water levels and flow conditions in both the main channel and the active floodplain branch system. Addressing the water deficit required technical measures on the Hungar-

ian side and an international agreement on the amount and seasonal distribution of water released into the Old Danube. Slovakia also had an interest in reaching a practical arrangement. The operation of the Gabčíkovo hydraulic complex had altered water distribution and ecological conditions on both sides of the border. The effects experienced in the Hungarian and Slovak floodplains therefore provided a shared reason for improving water management.

On April 19, 1995, the Governments of Hungary and the Slovak Republic signed the Agreement between the Government of the Slovak Republic and the Government of Hungary about Certain Temporary Measures and Discharges to the Danube and Mosoni-Danube (Agreement, 1995; SEA, 2010; Jakus et al., 2024). The agreement established the following seasonal discharge ranges for the Old Danube:

- winter period, October–March: 250–400 m³/s;
- summer period, April–September: 400–600 m³/s.

The agreed releases resulted in an average annual discharge of approximately 400 m³/s, with the actual discharge adjusted relative to the Danube discharge measured at Bratislava. The seasonal arrangement provided more water during the biologically active summer period while allowing releases to reflect changing river conditions. The agreement also allowed up to 150 m³/s of the water released at Čunovo to be directed into the Hungarian active and historical floodplain systems. The remaining discharge continued along the Old Danube. In addition, the supply to the Mosoni-Danube increased from approximately 20 m³/s to 43 m³/s, providing a more reliable water supply to the southern branch.

Another important element of the agreement was the establishment of a joint Hungarian–Slovak monitoring system. The monitoring program covered hydrological and environmental conditions, including surface-water discharge and levels, groundwater, water quality, sediment processes, and ecological changes. The two countries prepared annual monitoring reports, creating a shared evidence base for assessing the effects of water distribution and supporting later technical and operational decisions (Agreement, 1995).

The interim agreement did not resolve every legal, technical, or ecological question associated with the Gabčíkovo hydraulic complex. However, the agreement provided the practical water-sharing and monitoring framework needed to begin regulated operations and further develop the Szigetköz water-replenishment system.

3.5. Planning the dynamic water replenishment of Szigetköz

By raising water levels in the active and historical floodplain branch systems, the replenishment measures were also intended to strengthen hydraulic contact with the underlying aquifer and mitigate the groundwater decline caused by the diversion of the Danube. The design process determined the water depths and dynamically changing discharges required in the floodplain systems. The calculations were based on three main elements:

- water levels recorded at Dunaremete during the 1950s reference period;
- the water volumes available under the Hungarian–Slovak agreement;
- the ecological requirements agreed with stakeholders.

Target water levels in the Old Danube and the active floodplain branch system were determined using the Dunaremete records and longitudinal water-level profiles. The required discharges were calculated from the available hydraulic data and the previously defined ecological criteria. The international agreement set the upper limit on the amount of water available for distribution. Following the design phase, a comprehensive rehabilitation

plan was developed with stakeholder involvement and approved by the Hungarian authorities. Implementation proceeded in stages. The Upper Szigetköz system between Rajka and Ásványráró was constructed in 1995, while the Lower Szigetköz system was completed in 2015. Both the active and historical floodplain replenishment systems operate mainly by gravity, without the need for continuous pumping.

3.5.1. Active floodplain replenishment

Establishing a dynamic and adjustable water supply for the active floodplain first required higher water levels in the Old Danube. The Dunakiliti Barrage was brought into operation as part of the replenishment system, and a submerged weir was constructed in the main channel. Together, the two structures raised the upstream water level, creating a controlled backwater effect that allowed water to enter the floodplain branch system while maintaining flow in the Old Danube over the submerged weir. The principle of dynamic control is illustrated in Figure 47.

The submerged weir was designed with environmental integration and possible future removal in mind. Instead of conventional reinforced concrete, the structure was built from stone, gabions, and gravel fill.



Figure 47: a) Dynamic control of the active floodplain; b) overflow weirs to supply the active floodplain; c) submerged weir, and Dunakiliti Barrage

The average height of the weir is approximately 4 m above the riverbed, with a 1:3 upstream slope and a gentler 1:15 downstream slope. The construction process is documented in Figures 48–50, while the completed structure in operation is shown in Figure 51. A coarse stone surface on the downstream side dissipates the energy of the flowing water, reducing erosion and eliminating the need for a conventional stilling basin. In addition, it allows fish movement under suitable flow conditions, representing an early fish-passage solution in Szigetköz.

The resulting inflow into the active floodplain branch system is shown in Figure 52.

Two additional overflow weirs were constructed upstream of Dunakiliti to support water distribution. The Öregret and Benda overflow weirs were built at Danube river kilometres 1845.4 and 1845.9. Their crest levels and widths were selected to provide a reliable supply under changing hydrological conditions. Stone reinforcement protected the banks and structures against erosion. The wider arrangement of the Old Danube, the Hungarian and Slovak active floodplains, the Gabčíkovo supply canal, and the Hungarian historical floodplain replenishment system is shown in Figure 53. The overview demonstrates that the regional water bodies are spatially separated but remain connected through a system of controlled inflows, outlets, and hydraulic structures.



Figure 48: Construction of the submerged weir I



Figure 49: Construction of the submerged weir II



Figure 50: Construction of the submerged weir III



Figure 51: Operation of the submerged weir



Figure 52: The Dunakiliti Barrage and submerged weir raised upstream water levels, enabling inflow into the active floodplain branch system





Figure 53: Hydraulic control of the Danube and its floodplain systems between Čunovo and Vámoszabadi. From north to south, the figure shows the Gabčíkovo supply canal, the Slovak active floodplain branches, the Old Danube, the Hungarian active floodplain branches, and the Hungarian historical floodplain water-replenishment system. Riverbanks exposed by reduced discharge are marked in red. Insets show: a) the Öregrét and Benda overflow weirs; b) the Öregrét overflow weir; c) the Vörösfüzes and Paducos branch area; and d) the Denkpál branch-end closure

In some reaches, the water level in the Old Danube is approximately 1–3 m below that maintained in the floodplain branches. Closure weirs and guiding structures were therefore needed on both sides of the main channel to prevent water from draining back into the Old Danube and to retain water within the branch systems. Many earlier static, cascade-type structures were redesigned or removed. The revised arrangement allowed water to flow more freely during low-water conditions, while controlled overflow occurred during higher stages. Examples of the different hydraulic structures used within the system are presented in Figure 54.

A fish-passage facility was incorporated into the Denkpál branch-end closure, which is also represented among the structures in Figure 54. The passage allows fish and other aquatic organisms to move between the Old Danube and the branch system, reducing the barrier effect of the water-control structure. Fish passage, however, provides only one form of ecological connectivity. The wider design also had to maintain a range of floodplain habitats, including fast-flowing channels, slower side branches, backwaters, and partly isolated water bodies.

Stakeholders emphasized that habitat diversity should be retained within the replenished system. Fast-flowing branches provide different conditions from those in slow-flowing areas, where fine sediment and aquatic vegetation can develop. Backwaters with longer residence times can also provide feeding, nursery, and refuge habitats, provided that excessive stagnation and oxygen depletion are avoided. Öntési Lake, shown in Figure 55, illustrates one of the slower-flowing or standing-water habitats retained within the active floodplain mosaic. In 2018, an operational trial also examined whether the auxiliary navigation lock at Dunakiliti could support fish movement when operated as a fish lock. The trial indicated that suitable operation and attraction flow could provide an additional opportunity for longitudinal connectivity (Pannonhalmi and Dunai, 2021).

The final design combined these different habitat types within one regulated system. Engineers and water managers ensured that the structures could distribute water safely and maintain target levels, while ecologists and local stakeholders helped define habitat and access requirements.



Figure 54: Examples of complex hydraulic structures used to distribute and retain water within the active floodplain.



Figure 55: Öntési Lake (Öntési-tó) in the active floodplain



Figure 56: The Mosoni-Danube during low flow in 1991

The collaborative planning process therefore produced a multifunctional system that supports flood safety, water distribution, ecological connectivity, species diversity, and recreational use (Kertész, 2017). The active floodplain branch system was equipped with several types of hydraulic structures:

- low-threshold culverts that convey controlled amounts of water;
- stone weirs that block or guide flow where passage is not required;
- adjustable culvert–bridge combinations that allow flexible operation;
- low-threshold pipe sluices that function as weirs when closed;
- branch-end closures that prevent water from draining back into the Old Danube.

Smaller intake structures connected to neighboring systems provide additional, though limited, contributions to the overall water balance. Together, the structures shown in Figures 47–54 form an adjustable network capable of distributing water, maintaining ecological water levels, and supporting varied aquatic habitats.

3.5.2. Replenishment of the Mosoni-Danube

After 1905, the Mosoni-Danube received a regulated water supply through the Trianon Lock. The structure's threshold level was designed in relation to the natural water levels of the Danube. From the 1960s onwards, progressive deepening of the Old Danube riverbed reduced the water entering the Mosoni-Danube during low-flow periods. By the late 1980s, the supply could cease during prolonged low-water conditions. The condition of the Mosoni-Danube during low flow in 1991 is shown in Figure 56.

The diversion infrastructure created a new opportunity to provide water to the Mosoni-Danube and the historical floodplain channels. Water released from the Čunovo reservoir was conveyed through the supply channel and toe-drain system towards Dunakiliti and the Mosoni-Danube. Part of the transferred water was also available for replenishing the historical floodplain. The necessary intake structures had already been constructed as part of the Gabčíkovo–Nagymaros Project.

The remaining task was to establish the operating framework and determine how the available water should be divided between the Mosoni-Danube and the historical floodplain system. The resulting operating arrangement is illustrated in Figure 57.

The regulated supply provided more reliable water conditions in the Mosoni-Danube, particularly during periods when the Old Danube could no longer provide sufficient water naturally.

3.5.3. Historical floodplain

Water replenishment of the historical floodplain was implemented in two stages. The first stage, described in Section 3.1, connected the Zátonyi-Danube with the toe-drain channel shortly after the diversion of the Danube. A side spillway was constructed on the toe-drain channel and linked to the nearest floodplain branch by a short feeder channel. The second stage established seasonal water-level targets for both the Mosoni-Danube and the historical floodplain system. Stakeholders discussed and accepted the targets as part of a water-level management method that considered ecological needs together with operational safety.

The original drainage network had been designed to collect excess water and convey progressively larger volumes downstream. Water replenishment reversed the principal direction of operation by introducing water from upstream. Several existing structures, particularly in the upper part of the system, therefore required enlargement or modification to carry the increased flows. The reconfigured network also enabled water to return to long-abandoned oxbows. Lipót Oxbow Lake, shown in Figure 58, is an example of a historical floodplain water body supported by replenishment.

Continuous replenishment created opportunities for several uses. Ecological rehabilitation remained the primary objective, while the restored channels and water bodies also supported fishing, recreation, tourism, and limited irrigation. The conversion of the drainage network marked a significant change in water management. A system originally designed mainly to remove excess water became a multifunctional network capable of supplying, distributing, retaining, and, when necessary, draining water.

The geographical extent of the active and historical floodplain measures completed during the first implementation phase is presented in Figure 59.

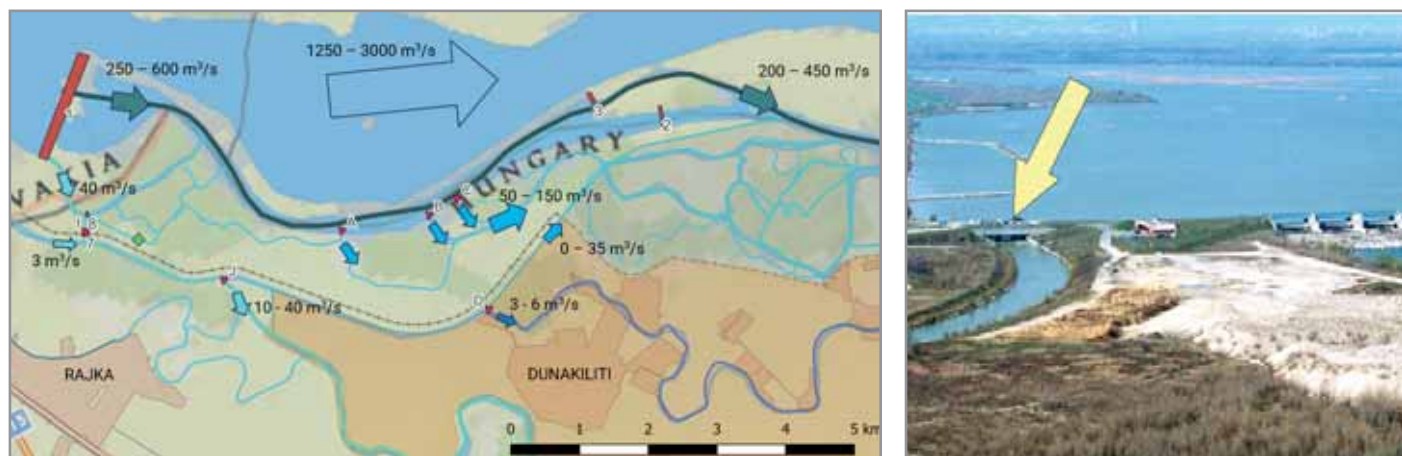


Figure 57: Operation of the Mosoni-Danube water-supply system, shown with blue and yellow arrows (Dunai, 2024)



Figure 58: Lipót Oxbow Lake (Lipóti morotva) in the historical floodplain

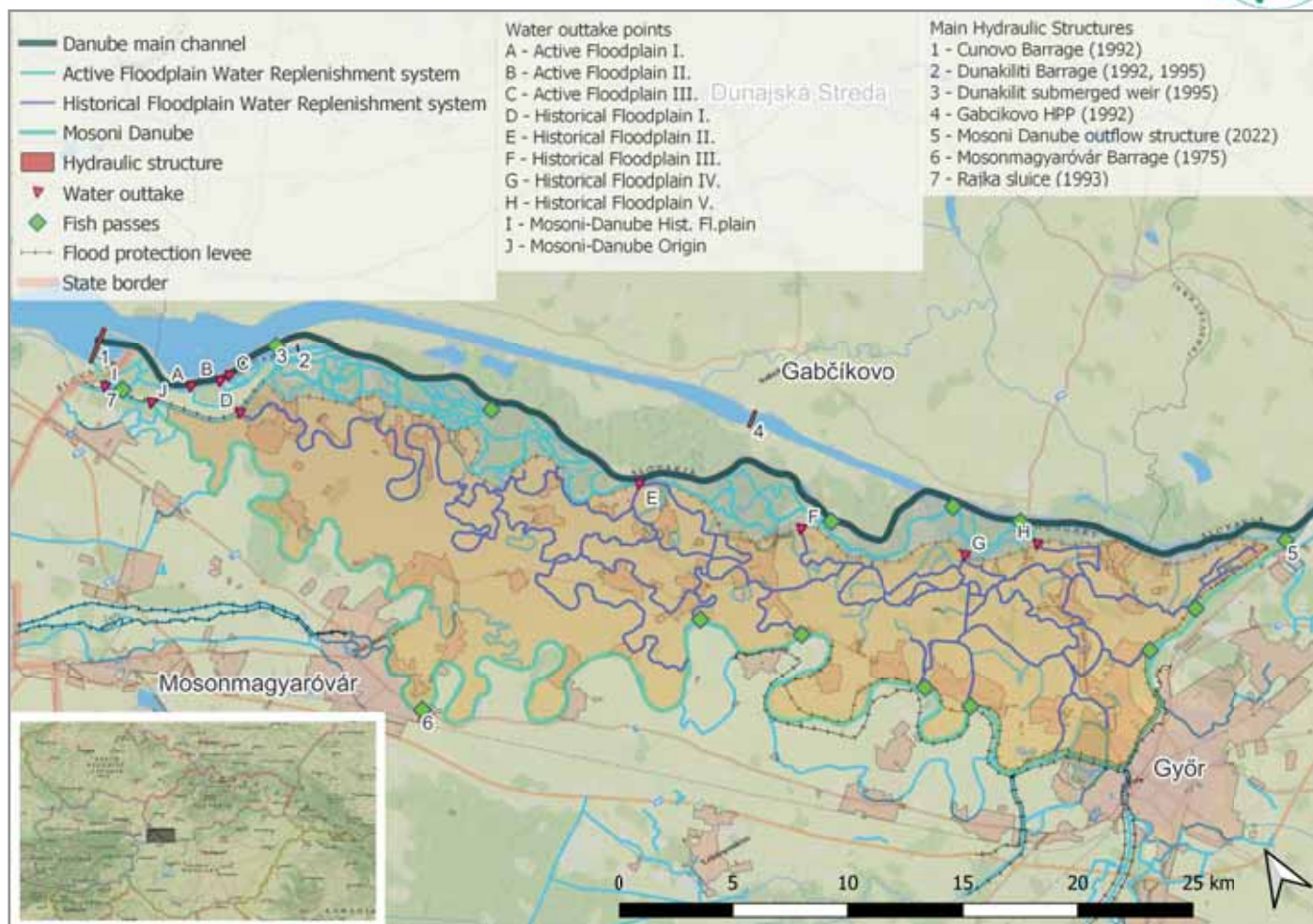


Figure 59: The extent of the first phase of water replenishment completed by 1995.

4. TEST OPERATION (1995–2000)

This chapter presents the operational testing of the Szigetköz water replenishment system between 1995 and 2000, including its operating rules, monitoring framework, hydrological and ecological impacts, and performance-based adjustments.

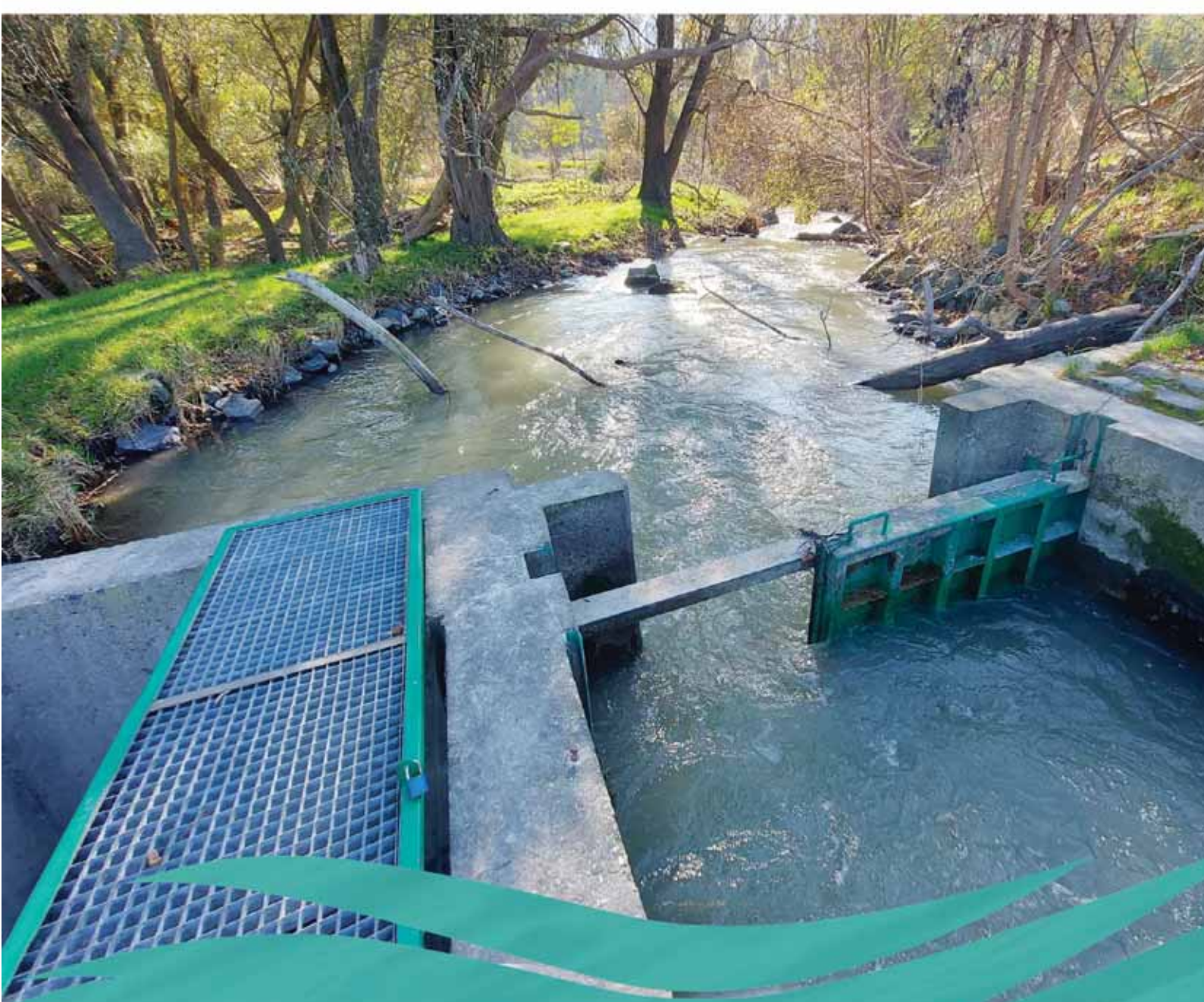


Figure 60: Denkpál fish passage



Transferable lesson 4 — Use test operation and monitoring to refine permanent operating rules

Challenge addressed

The actual performance of a floodplain system may differ from design calculations because water losses, channel resistance, sedimentation, groundwater response, and ecological conditions vary by location and season.

Approach used in Szigetköz

Between 1995 and 2000, the water-replenishment system operated under a test regime. Operators adjusted water distribution according to Danube discharge and seasonal conditions. Monitoring compared planned and measured water levels, supported adjustments to individual structures, and provided data for calibrating the hydraulic model. Separate winter and summer model parameters were introduced because infiltration and evapotranspiration losses were greater during warmer periods. The test phase also identified system limitations. Some branches remained below their intended high-water targets, and low flows could not always provide the planned velocities and residence times. The results showed which problems could be corrected through operation and which required structural improvements.

General principle

Initial operation should be treated as a structured learning period. Permanent operating rules should be based on measured performance under different seasonal and hydrological conditions, not only on design assumptions.

Conditions for transfer

The approach requires adjustable structures, baseline data, representative monitoring, calibrated models, and sufficient time to test different flow conditions. Monitoring results must be used directly to revise water allocation, structure settings, and operating rules.

Suggested indicators

Target and measured water levels, branch discharges, flow velocity, residence time, groundwater levels, water quality, sedimentation, habitat response, and the frequency of operational adjustments.

Test operation (1995–2000)

The test operation of the new system played an important role in maintaining the trust and professional credibility established during the design phase. The test period also provided the measurements and operational experience needed to compare the planned conditions with the system's actual performance and to refine its operation. Following the introduction of water replenishment, visible improvements in channel and wetland conditions occurred across both the active and historical floodplains. These changes were directly experienced by stakeholders and local communities, reinforcing confidence in the effectiveness of the implemented measures. The Denkpál fish passage, one of the structures supporting aquatic connectivity within the active floodplain system, is shown in Figure 60.

4.1. Water replenishment during test operation

The water replenishment system was gradually developed and refined between 1995 and 2000. Its operation was linked to daily discharge conditions measured at Bratislava (Dévény). The North-Transdanubian Water Directorate operated the system based on the relationship between Danube discharge and the required compensation flows into the branch systems. The operational regime was defined in consultation with stakeholders. The year was divided into winter and summer operating periods, with transitional periods in between. Seasonal operating discharges were adjusted to flow conditions at Bratislava, ensuring that water management followed a consistent, predictable framework while still reflecting natural variability. The arrangement allowed operators to respond to daily changes in the Danube while maintaining an agreed seasonal framework for water distribution.

4.2. Impact of the Water Replenishment System

A comprehensive monitoring system was established to assess the impacts of water replenishment and to ensure transparency. Hungary and Slovakia agreed on joint monitoring activities, including shared measurements, data exchange, and evaluation. In addition to documenting water distribution, experts from both countries conducted joint field sampling and produced annual reports *Slovak–Hungarian Environmental Monitoring on the Danube* (2006).

Since 1995, monitoring has provided a long-term dataset for evaluating environmental conditions in the Szigetköz region. The program covered surface-water quantity and quality, groundwater levels and chemistry, soil moisture, forestry conditions, and biological indicators (see Appen-

dix 1). The monitoring framework did not evaluate individual parameters in isolation. The ECONTACT project assessed surface-water condition by combining evaluations of hydromorphological, physicochemical, and biological elements, including aquatic vegetation, macroinvertebrates, and fish (Pannonhalmi, 2005). Hydromorphological elements describe the physical form of the river system, its flow conditions, and the connections among channels and habitats. The framework treated these components as interdependent, recognizing that chemical measurements alone do not fully describe a water body's ecological condition.

The monitoring results highlighted strong interactions between surface water and groundwater, influenced by geological conditions and flow dynamics. Local riverbed conditions also affected whether some monitoring methods could be applied reliably. Fine sediment could clog the riverbed and the filter zone around monitoring probes—a process known as colmation—and prevent representative sampling (Szűcs, 2018).

4.2.1. Surface water

During the monitoring years, controlled flow conditions strongly influenced surface water dynamics in the Szigetköz region (Szűcs A., 2018). Gauges across the region continuously recorded water levels, allowing detailed observations in the main river and floodplain systems. River regulation, upstream barrages, and flow diversion also modified sediment transport. Reduced coarse-sediment supply contributed to riverbed incision in parts of the main channel, while suspended fine sediment accumulated in some floodplain branches and low-velocity areas during floods or prolonged inundation. These processes affected channel morphology, hydraulic connectivity, substrate composition, and exchanges between surface water and groundwater.

Main Danube (Old Danube)

Key observations were made along different sections of the Old Danube:

- **Upstream section: (1851–1843 rkm)**
The combined operation of the Dunakiliti Barrage and the submerged weir resulted in slow flow and significant fine-sediment deposition. The groundwater table was often deep, and algal growth along the banks was observed. Downstream of the submerged weir, flow velocity was stable, but extensive sediment accumulation and algal proliferation occurred near the riverbanks.
- **Middle section: 1841–1825 rkm**
Flow is mainly controlled by water released at Čunovo. Locally stronger currents led to the formation of gravel bars and algal layers, while groundwater seepage remained active.

- **Transitional section (next ~5 km):1825–1820 rkm**
Balanced water levels were observed in early spring and late autumn, while backwater effects from the Gabčíkovo tailrace influenced summer high-water conditions.
- **Lower section:1820–1811 rkm**
This reach is strongly affected by the backwater effect of the Gabčíkovo HPP, with widespread sedimentation, development of vegetated gravel and sand bars, and visible seepage points marked by iron–manganese staining.

The monitoring locations used to document these spatial differences are shown in Figure 61.

Active Floodplain

The active floodplain branch system upstream from Ásványráró was entirely influenced by dynamic water regulation. Annual water-level fluctuations typically did not exceed 1.0–1.2 m. The average water-level difference between early spring lows and early summer highs was about 70–90 cm. Flow velocities above 1.0 m/s occurred only locally—between Dunakiliti and Doborgaz Island, below sluices, or in connecting branches. Monitoring showed that periodic inundations did not significantly alter the overall pattern of surface water movement. Sediment layers remained intact, and notable water and sediment movement was confined to areas downstream of weirs.

Historical Floodplain

In the historical floodplain, water-level fluctuations in channels generally remained below 0.5 m. The controlled water level at Rajka determined the amount of water entering the system. Watercourses in this area are mainly slow-flowing or stagnant, impounded water bodies.

Mosoni-Danube

In the Mosoni-Danube, flow is fully regulated up to Mosonmagyaróvár. Water levels stabilized above historical averages, but major natural Danube flood peaks were absent. In addition, nine monitoring points were established in 1995 for detailed sedimentation–erosion and infiltration–seepage studies.

The monitoring results show that water replenishment restored and stabilized surface-water conditions in large parts of the system, but it did not recreate the full range of natural water-level fluctuations, flood pulses, and sediment movement that had characterized the floodplain before diversion.

4.2.2. Groundwater

Before 1992, groundwater levels closely followed the natural fluctuations of the Danube. After the diversion, water levels in the Old Danube declined, and the hydraulic connection between the river and the aquifer weakened across substantial parts of Szigetköz (Bárdossy and Molnár, 2004). The strongest effects occurred near the Old Danube, where the reduced river stage altered or locally reversed the former direction of groundwater flow.

Long-term monitoring data confirm that groundwater levels decreased by 30–150 cm in many areas, with even larger declines observed in zones adjacent to the Old Danube where flow conditions changed after the diversion (KvVM, 1996; MTA Szigetközi Munkacsoport, 1998). At the same time, groundwater variability also declined: both the amplitude of annual fluctuations and their variability were reduced, indicating a less dynamic system that became less responsive to natural hydrological processes.

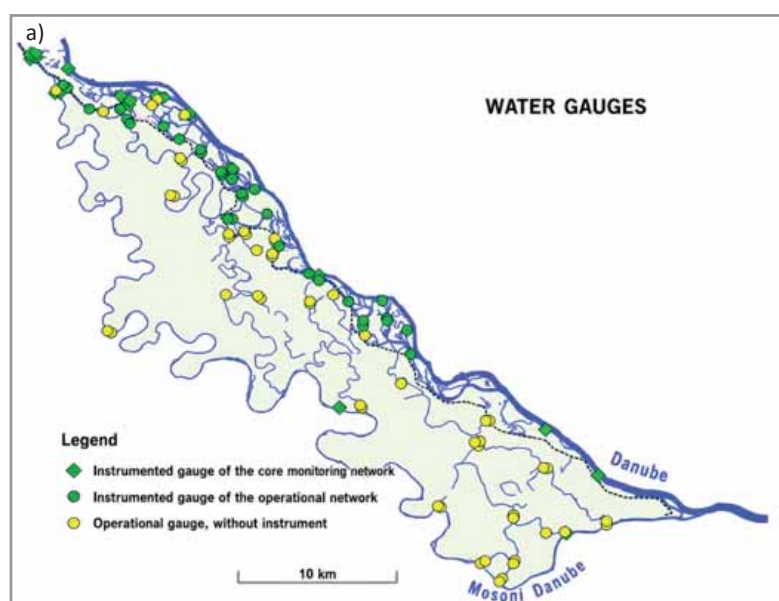


Figure 61: a) Locations of surface-water level gauging stations in Szigetköz. Gauging stations are monitoring points where river or channel water levels are measured regularly or continuously to track changes over time (Szűcs, 2009); b) Old Danube gauge at Doborgaz

The reduction in seasonal variability was especially important because groundwater-dependent soils, forests, wetlands, and agricultural areas had previously responded to the changing stages of the Danube. The effect was most pronounced in summer, when reduced recharge combined with higher evapotranspiration limited the system's ability to buffer extreme conditions (Bárdossy and Molnár, 2004).

The water-replenishment system mitigated part of the decline by supplying water to the active and historical floodplain branch systems and supporting groundwater recharge in directly affected areas. Controlled flows introduced into the Mosoni-Danube and the floodplain branches helped stabilize groundwater levels near supplied channels and water bodies. Monitoring results showed that water levels in oxbows and side branches recovered where direct supply was ensured (Jakus et al., 2024, Chappon et al., 2024a).

The effects nevertheless varied spatially and seasonally. Recovery was generally clearer near directly supplied branches and water bodies, while groundwater deficits and dampened fluctuations remained in some areas, particularly in Upper Szigetköz and near the Old Danube. In contrast, downstream areas influenced by the Gabčíkovo hydraulic complex exhibited more dynamic groundwater behavior (Koltai, 2003). Figure 62 shows the groundwater potential pattern after water replenishment of the branch systems. Groundwater potential lines indicate the direction in which groundwater tends to move through the aquifer.

The monitoring results therefore indicate partial recovery and stabilization rather than a uniform return to pre-diversion groundwater conditions. The replenishment system was most effective near directly supplied branches. At the same time, the reduced stage of the Old Danube continued to influence groundwater levels and seasonal variability in other parts of Szigetköz.

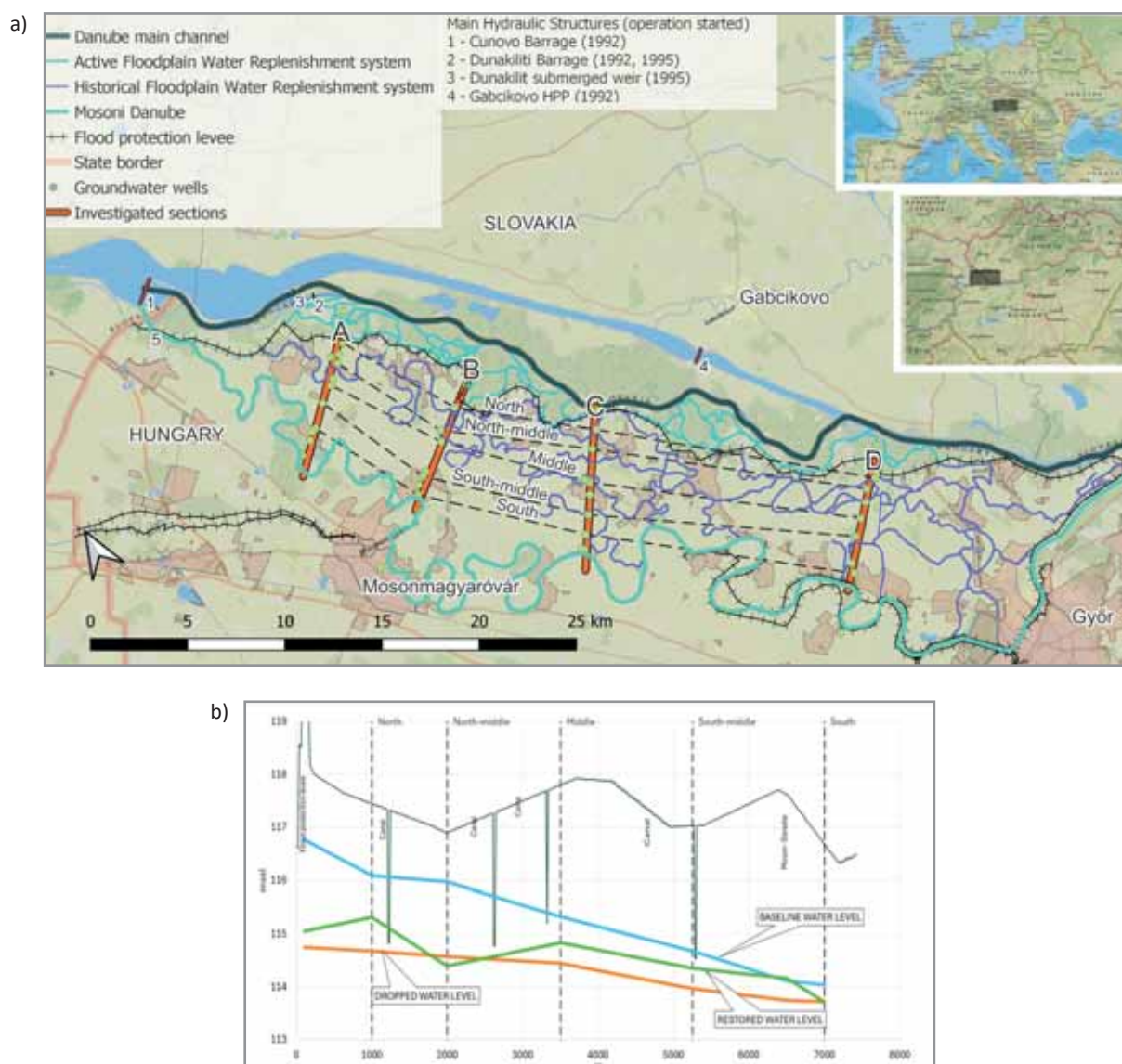


Figure 62: a) Cross-section locations for groundwater evaluation; b) Groundwater potential lines after water replenishment of the branches at cross section C (Chappon et al. (2024a))

4.2.3. Water quality

Water quality in Szigetköz is primarily influenced by the quality of the Danube water entering the system, but it is further modified by local hydraulic conditions, sedimentation, water residence time, tributary inflows, agricultural land use, and wastewater inputs.

Long-term observations at the Rajka section indicate substantial improvement in several chemical water-quality parameters compared with the more polluted conditions of the 1960s–1980s. Indicators of municipal pollution, nutrient loading, organic matter, oils, and phenolic compounds generally decreased, partly due to industrial restructuring and improved wastewater treatment in upstream urban areas, particularly Vienna and Bratislava (Pannonhalmi and Varga, 2021). Long-term monitoring also recorded improvements in chemical oxygen demand (COD), total organic carbon (TOC), nutrient concentrations, and bacterial indicators (Szűcs, 2018; KvVM, 1996).

Later monitoring conducted in 2006 and 2007 generally found favorable oxygen and nutrient conditions in the main Danube channel and in many parts of the replenishment system. Nitrate remained below the applied undesirable threshold, while ammonium and nitrite occurred mainly at low concentrations. Chlorophyll-a and oxygen saturation nevertheless showed substantial spatial and seasonal variability. The chemical monitoring results indicate generally favorable conditions in the main channel, together with greater spatial and seasonal variability in the slower-flowing parts of the branch system.

Water quality in the side branches generally reflects that of the main river because of the controlled water supply introduced through the replenishment system. At the same time, spatial variability remains significant. In the Mosoni-Danube, local inputs from tributaries, settlements, and agricultural areas contribute to more variable conditions and occasional localized pollution (Szűcs, 2018).

Hydraulic conditions also play a key role in shaping water quality. Reduced flow velocities and increased sedimentation in regulated sections—such as upstream of weirs or in reaches affected by raised downstream water levels—promote the accumulation of nutrients and fine sediments, which can enhance eutrophication processes and algal growth (Szűcs, 2018). Sedimentation processes also influence filtration and the exchange between surface water and groundwater, further modifying local water-quality conditions.

Groundwater quality in Szigetköz is generally stable, although its chemical composition varies across the region and suitability depends on the intended use and local conditions. Elevated concentrations of iron and manganese are common due to the geochemical characteristics of the alluvial sediments and the reducing conditions in the aquifer (KvVM, 1996; Szűcs, 2018). Variations in nitrogen compounds and organic matter indicate the influence of agricultural activities and wastewater inputs, particularly in areas with intensive land use.

Long-term monitoring shows that groundwater composition is strongly influenced by interactions with surface water, with seasonal and spatial variations reflecting infiltration processes and residence times (Szűcs, 2018). Changes in groundwater-flow patterns caused by the diversion of the Danube and the operation of the replenishment system have further modified recharge conditions and mixing processes, leading to spatial differences in groundwater quality across the region (Bárdossy and Molnár, 2004; ÉDUVIZIG, 2004).

The water-quality results therefore show two simultaneous trends. The quality of the Danube water entering Szigetköz improved substantially over the long term. At the same time, slow flow, prolonged residence time, sediment accumulation, and local pollution sources continued to create water-quality risks in particular branches and reaches.

4.2.4. Ecological impacts

The ecological consequences of the Danube diversion in 1992 were immediate and severe in the Szigetköz floodplain. The loss of surface-water supply caused the upper branch system to dry out almost completely, eliminating spawning and feeding grounds for fish and drastically reducing amphibian and wetland habitats (Kerekes, 1999). Terrestrial impacts were also significant: declining groundwater tables reduced soil moisture, weakening forests, pastures, and agricultural lands, particularly in the upper floodplain (KvVM, 1996).

The replenishment system, operational from the mid-1990s, aimed to restore ecological functions by returning water to side branches and oxbows. As replenishment flows gradually increased, monitoring showed a partial recovery of aquatic habitats. Fish returned to some of the rewatered branches, and amphibians and waterfowl once again used floodplain wetlands as breeding and feeding areas (ÉDUVIZIG, 2004). Vegetation also responded: oxbow lakes and slow-flowing branches developed typical aquatic plant (macrophyte) communities, and riparian forests regained soil moisture, helping stabilize oak–ash–elm groves along the Mosoni-Danube (Jakus et al., 2024).

Overall, the replenishment system mitigated some of the most severe ecological losses and helped maintain characteristic floodplain habitats and species. However, the ecological system did not return to its pre-diversion state. Natural flood pulses remained weaker, seasonal water-level variability was reduced, and full ecological connectivity with the Old Danube was not restored (KvVM, 1996; ÉDUVIZIG, 2004; Jakus et al., 2024). Reduced water-level variability and shorter inundation periods reduced habitat diversity and productivity.

Key species, such as sturgeons (*Huso huso* and *Acipenser stellatus*), remained absent, and invasive species expanded into modified habitats (Guti, 2020). Forest composition shifted toward planted willow and poplar stands, while natural willow–poplar–alder groves became fragmented.

Later biological monitoring in 2006 and 2007 showed that equivalent responses across all biological quality elements did not always accompany improvements in chemical water quality.

A New Bat Species in the Szigetköz – The Story of the Pond Bat's Appearance

In the summer of 2020, researchers made a remarkable discovery in the Szigetköz Natura 2000 protected area: the first recorded occurrence of the pond bat (*Myotis dasycneme*). This rare, water-dependent bat species typically hunts insects over lakes, backwaters, and river branches across Europe. The first detections were made through acoustic monitoring, and later several individuals were captured using mist nets — including females — suggesting that this is not merely a transient population but a potential breeding colony.

The finding represents a major conservation success, as the pond bat had previously been known only from eastern and northern Hungary and had not been observed in the Szigetköz for decades. Its reappearance indicates an improvement in local wetland and floodplain habitats, partly due to water replenishment systems and side-channel restoration measures implemented in recent years. The mosaic landscape of the Szigetköz — combining open water, riparian forests, abundant insect populations, and hollow trees — provides ideal conditions for feeding and reproduction.

According to researchers, this return is one of the clearest indicators of successful habitat management: wherever natural water dynamics and forest processes are restored, sensitive species tend to follow. The presence of the pond bat in the Szigetköz is therefore not only a zoological curiosity but also a hopeful sign — evidence that the Danube's floodplain ecosystem can still regenerate when given the opportunity.

Fertő–Hanság Nemzeti Park facebook page (2020.09.04.)



The 2007 results must also be interpreted within their methodological context. Type-specific reference conditions and complete Water Framework Directive classification methods were not yet available for all relevant biological quality elements. The monitoring data therefore supported ecological interpretation but did not always permit a complete formal classification of ecological status or ecological potential (Ördög and Koltai, 2008).

After the initial activation of the water replenishment system, deviations from the planned target water levels were detected in several areas of the floodplain. Continuous field measurements were conducted to identify the causes, and minor technical adjustments were made to individual control structures to correct the discrepancies. Further adjustments based on the monitoring results were then made to ensure that the desired water levels could be maintained throughout the year under different hydrological conditions.

To better understand the hydraulic behavior of the system, the entire branch network was modeled and calibrated using MIKE 11, a one-dimensional, unsteady-flow model designed for complex river systems.



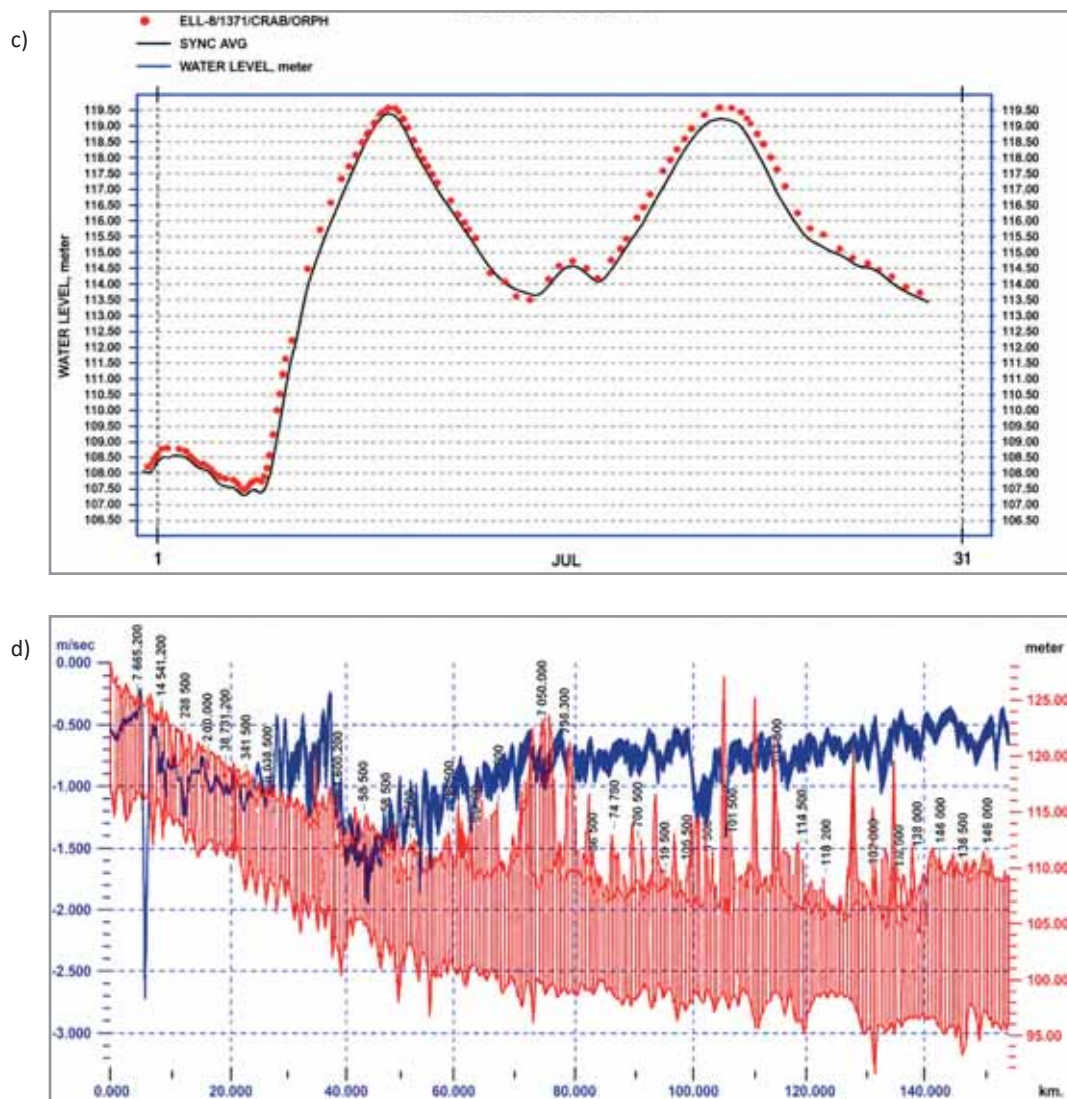


Figure 63: (a-d) Modeling and calibration of the active floodplain branch system, showing typical flow velocities and water levels

The model simulated how water levels and discharges changed over time along the connected channel network. The modeling work provided insight into the system's hydraulics, including mean channel velocities, flow distribution, and local water-level dynamics across the floodplain. The calibration process relied on long-term hydrological measurements and water-level records, enabling comparison between modeled and observed data. Seasonal calibration revealed that summer conditions required higher inflows than winter conditions because infiltration and evapotranspiration losses were greater during the warmer months. Consequently, two parameter sets were established—one for winter and another for summer—improving the precision of operational flow regulation. The model calibration and the resulting typical flow velocities and water levels are presented in Figure 63.

Key input parameters included:

- Rating curves developed for representative cross-sections;
- Measured infiltration and leakage losses across the floodplain;

- Relationships between inflow and local water-level responses;
- Observed data from the joint Hungarian–Slovak monitoring network;
- Hydraulic principles governing channel resistance and energy gradients.

The existing channel closures and hydraulic structures allow a maximum operational replenishment flow of approximately 250 m³/s. Because hydraulic resistance varies across the branch network, different discharges are required to achieve comparable water levels in different sections. Low-water conditions generally require flows of approximately 20–50 m³/s, while average water levels require about 80–170 m³/s. Even at the maximum operational flow, some branches remain approximately 1.5 m below the intended ecological high-water targets.

The highest water demand occurs in the upper floodplain, requiring optimized use of existing diversion options and local redistribution of flow. During low-flow operation, the target velocities and residence times cannot always be maintained, which may adversely affect oxygen conditions

and water quality. Further structural improvements and local measures to strengthen hydraulic connectivity may therefore be required to maintain acceptable ecological and water-use conditions under changing circumstances.

The MIKE 11 simulation results also revealed significant spatial variation in flow velocities across the branch system. These differences, both between and within branches, created heterogeneous hydraulic and ecological conditions. The resulting differences in flow conditions created a range of hydraulic habitats across the active floodplain. Later biological monitoring found differences in aquatic vegetation and macroinvertebrate communities between fast-flowing, shallow, and nearly stagnant areas (Pannonhalmi, 2007; Ördög and Koltai, 2008). Operation at Dunakiliti had to be adjusted daily according to the Danube discharge recorded at Bratislava and the applicable seasonal operating period, as shown in Figure 64.

Figure 64 illustrates the daily operational control process for the Szigetköz water replenishment system. Based on the agreed water-sharing framework and the established design principles, a dedicated calculation tool—an Excel-based model—was used to determine the required discharge for the system. The operator used the tool to translate upstream flow data into target flow allocations for the floodplain branches. At the same time, the control interface displayed on the main screen provided real-time information on water levels, flow conditions, and the status of hydraulic structures within the system. The displayed information allowed the operator to verify that the calculated discharge was being implemented correctly and continuously and to adjust settings if necessary. The integration of calculation and monitoring allowed the system to operate in accordance with both ecological objectives and hydraulic constraints.

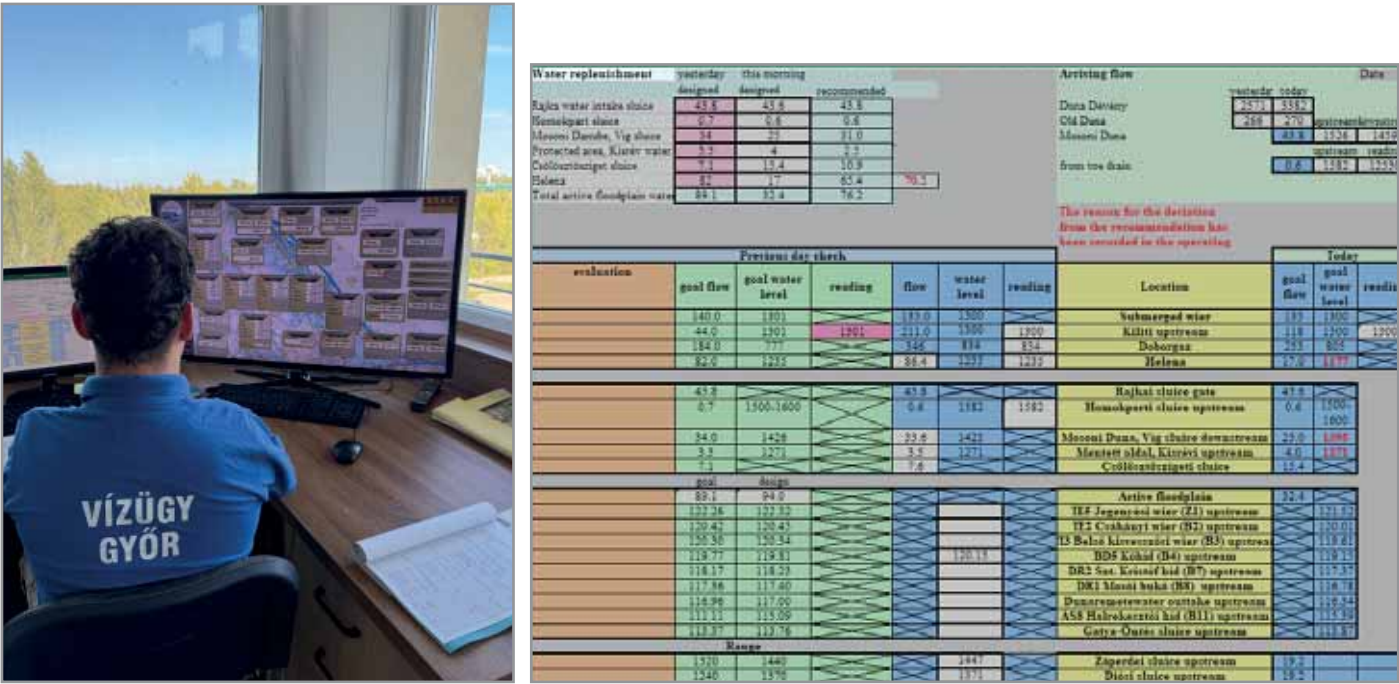


Figure 64: Daily water-level control at Dunakiliti

5. ESTABLISHING THE OPERATING REGULATIONS AND APPLICATION FOR AN OPERATING PERMIT

This chapter presents the operational testing of the Szigetköz water replenishment system between 1995 and 2000, including its operating rules, monitoring framework, hydrological and ecological impacts, and performance-based adjustments.



Figure 65: Flow in the toe-drain channel and its connection to the supply channel at the Rajka sluice gate



Transferable lesson 5 — Convert competing needs into operating rules

Challenge addressed

Floodplain systems must support ecological restoration, agriculture, drainage, forestry, recreation, fisheries, and flood protection. These functions may require different water levels, flow conditions, and operating periods, while available water and hydraulic capacity remain limited.

Approach used in Szigetköz

Value analysis was used to identify stakeholder needs, rank the expected functions of the system, and make conflicts explicit. Separate function trees were prepared for the active and historical floodplains. They showed why each function was needed, how it could be provided, and where objectives conflicted. Conflicts were addressed by separating functions in space or time, defining technical or ecological limits, and introducing engineering or compensation measures where necessary. The process created an agreed basis for translating stakeholder priorities into operating rules.

General principle

Operating rules should reflect agreed priorities and acceptable compromises, not only hydraulic feasibility. The decision process should clearly distinguish stakeholder preferences, legal obligations, scientific evidence, and technical constraints.

Conditions for transfer

The approach requires representative stakeholder participation, transparent prioritization, documented conflicts, and a clear link between agreed functions and measurable operating parameters.

Suggested indicators

Stakeholder participation, agreed function priorities, documented compromises, unresolved conflicts, and the extent to which operating rules reflect the agreed priorities.

Establishing the operating regulations and application for an operating permit (2000)

The development of the operating regulations and the finalization of the permit process followed a structured, multi-step approach focused on sustainable water management. Previous studies (see Chapter 4) were reviewed to incorporate results from monitoring, hydraulic modeling, and operational experience gained during the test phase. Stakeholders were then identified, and their diverse interests—ranging from ecological protection to agricultural use—were considered in the planning process. A consensus-based approach was developed through continuous consultation, allowing potential conflicts to be identified and addressed early. Engineering analyses provided the technical and ecological foundation for decision-making, while the test-operation results highlighted areas requiring adjustment. By comparing water demand with system capacity, the final concept established operating rules to balance ecological, agricultural, water-management, and regulatory requirements within the system's technical limits. The connection between the supply channel and the toe-drain system at Rajka is shown in Figure 65.

5.1. Operating permit

Following the completion of the test operation, an operating permit had to be obtained from the water authority. The application included the as-built documentation of the system, records of the structures and channels as they were actually constructed, and the proposed operational regulations. The following sections focus on the development and finalization of these operational rules (Janák et al., 2014). The main steps in the permit-development process are shown in Figure 66.

The process began with a stakeholder meeting, at which the operational constraints were clearly outlined.

These included limited water availability, as a significant portion of the Danube discharge continued to be diverted to the Gabčíkovo HPP, incomplete spatial coverage of the replenishment system within the Szigetköz floodplain, and financial limitations affecting maintenance and future development. Based on these constraints, the priorities for water replenishment were reassessed, and the ranking of stakeholder demands was reviewed with external experts. The objective was to develop operating rules that reflected the available water and system capacity while maintaining the functions previously agreed with stakeholders.

5.2. Applying value analysis

Stakeholders define the water replenishment system through the functions they expect it to fulfill. The objective is to support these functions while minimizing conflicts and resource use. Value analysis provides a structured decision-support framework centered on functions and their efficient delivery. Originally developed for product design, the method focuses on meeting user needs cost-effectively and has since been widely applied to complex, open-ended problems where both objectives and solutions are uncertain.

Value analysis (SAVE, 2015):

1. Start from the needs and expectations of users and stakeholders.
2. Define the tasks and functions necessary to satisfy these needs by developing a functional model and process for the object under study.
3. Examine the required performance level, properties, and functional scope.
4. Evaluate the quality of current solutions by analyzing their functions, costs, and organizational relationships, and identify those that deliver poor quality or incur disproportionate costs.
5. Assess the expenses associated with each function.
6. Determine the optimal combination of solutions for delivering each function.

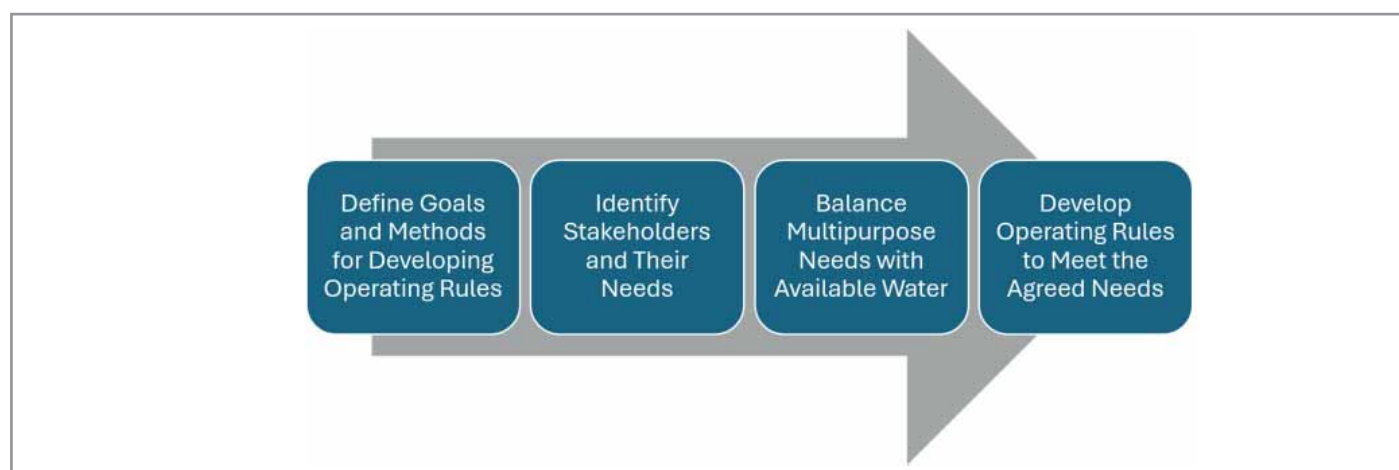


Figure 66: Workflow for the development and approval of the operating permit

In the case of the Szigetköz water replenishment system, the following methodological steps were applied: determining the function tree, identifying and managing conflicts, setting priorities, and defining design parameters (e.g., target water levels). The first goal was to establish the ranking of individual stakeholder needs and the functions derived from them. The ranking of the primary functions was determined using the paired comparison method (see Appendix 2). To define the desirable conditions for restoration, stakeholders jointly prioritized various needs and requirements following the principles of value analysis. The prioritization integrated the perspectives of the identified stakeholder groups into the evaluation process.

Stakeholder categories were as follows:

- Nature conservation
- Environmental protection, water quality protection
- Forestry
- Hunting
- Agriculture
- Fishing
- Tourism
- Water management

Separate function trees were prepared for the active and historical floodplains to clarify the main expectations (functions) and the tasks required to achieve them. Moving to the right within the function tree answers the question “How can the objective be achieved?” by outlining the required tools and methods. Moving to the left answers the question “Why is the intervention needed?” by explaining its purpose.

The function trees also played an important role in identifying and understanding conflicts between stakeholder objectives. When such conflicts emerged, different resolution strategies were applied to reach balanced compromises. In some cases, functions were separated in space or time to avoid interference. In other cases, quality or biological limits were established to ensure sustainability. Where appropriate, engineering solutions were introduced to meet technical requirements, and compensation measures were applied to offset unavoidable impacts.

A practical example was the historical floodplain, where conflicting needs for water retention and drainage were reconciled through operating limits and adjustable structures. Residence-time limits reduced the risk of eutrophication, while sluices and weirs regulated water levels and allowed excess water to be removed when necessary.

5.2.1. Historical floodplain

The primary goals of the historical floodplain water replenishment were:

- Prevent further damage
- Restore the former mosaic-like character of the Szigetköz landscape
- Restore wetland habitats on the floodplain
- Recreate the former water dynamics in the water bodies of the historical floodplain.

To support these goals, a function tree was developed for the historical floodplain (Figure 67). The function tree links broad rehabilitation objectives to the practical measures required to achieve them. It also shows where a single measure serves multiple functions and where competing requirements must be separated in space, time, or operation.

Among the additional functions, the preservation and enhancement of agricultural potential were key objectives. Water remains the decisive factor for maintaining and enhancing agricultural productivity, with precipitation playing a dominant role and groundwater levels exerting significant influence in certain areas. The function tree for additional objectives is shown in Figure 68.

The drainage of harmful excess water remains a fundamental function of the historical floodplain system, particularly in areas where rising flood levels and insufficient past developments have increased the risk of inland water damage. The risk is especially evident in the protected area between the Danube flood protection embankment and the Szavai main channel, where intermittent waterlogging reduces land usability and poses risks to settlements and infrastructure.

At the same time, the rehabilitation concept requires that the system no longer operate as a single-purpose drainage network. Instead, the system must function as a multifunctional water-management system capable of simultaneously supporting water retention, water supply, and ecological restoration. While the drainage of excess inland water remains a core function, controlled water retention and redistribution have become increasingly important. A conflict therefore arises between the need for rapid, safe removal of excess water and the objective of retaining water to restore wetland habitats and landscape structure. Within the value-analysis framework, the conflict is addressed not by eliminating one function in favor of the other, but by integrating both into a regulated and adaptive system.

Figure 69 illustrates examples of this approach in the historical floodplain.

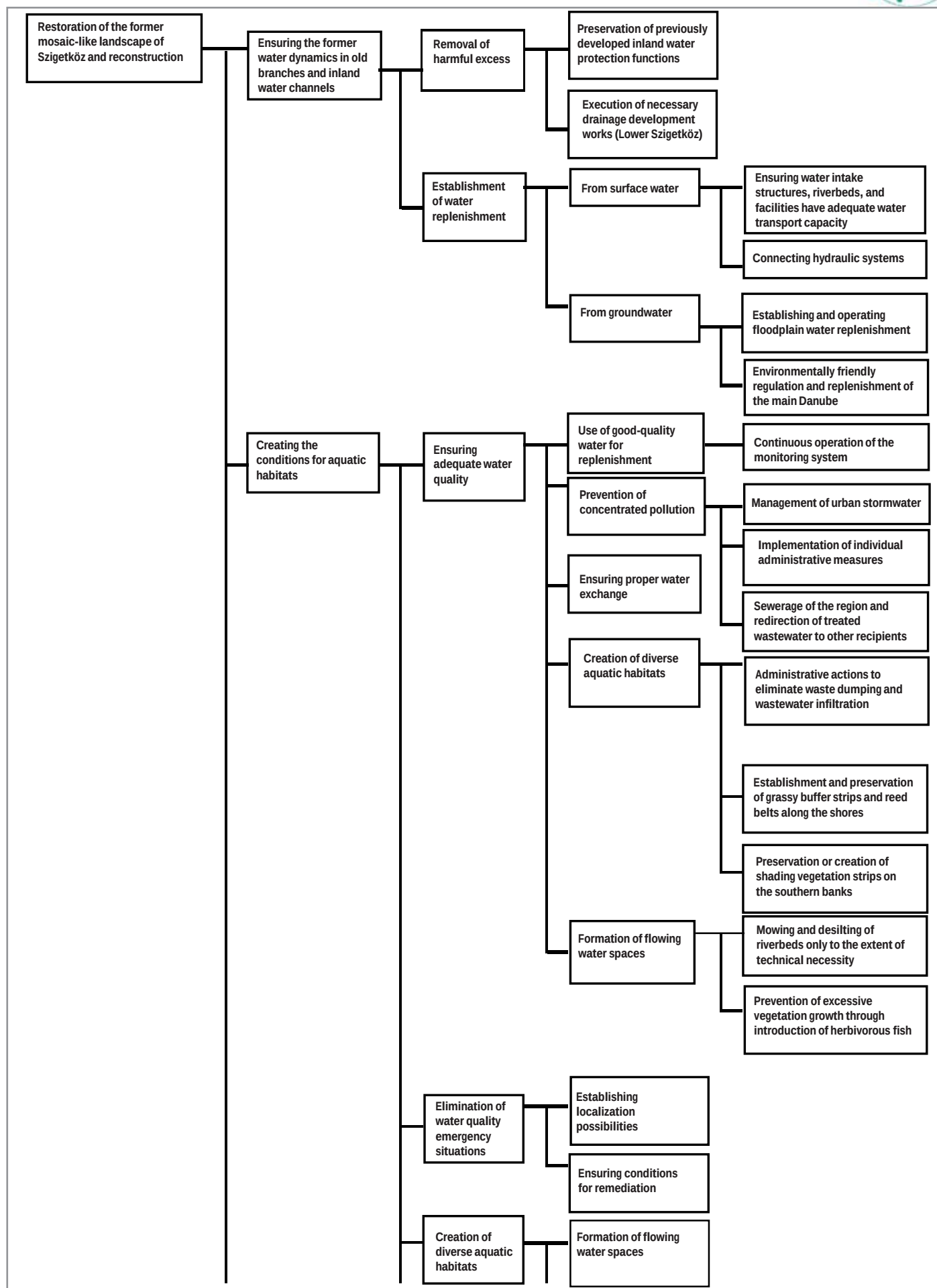


Figure 67: Function tree for the historical floodplain (Dunai, 1995)

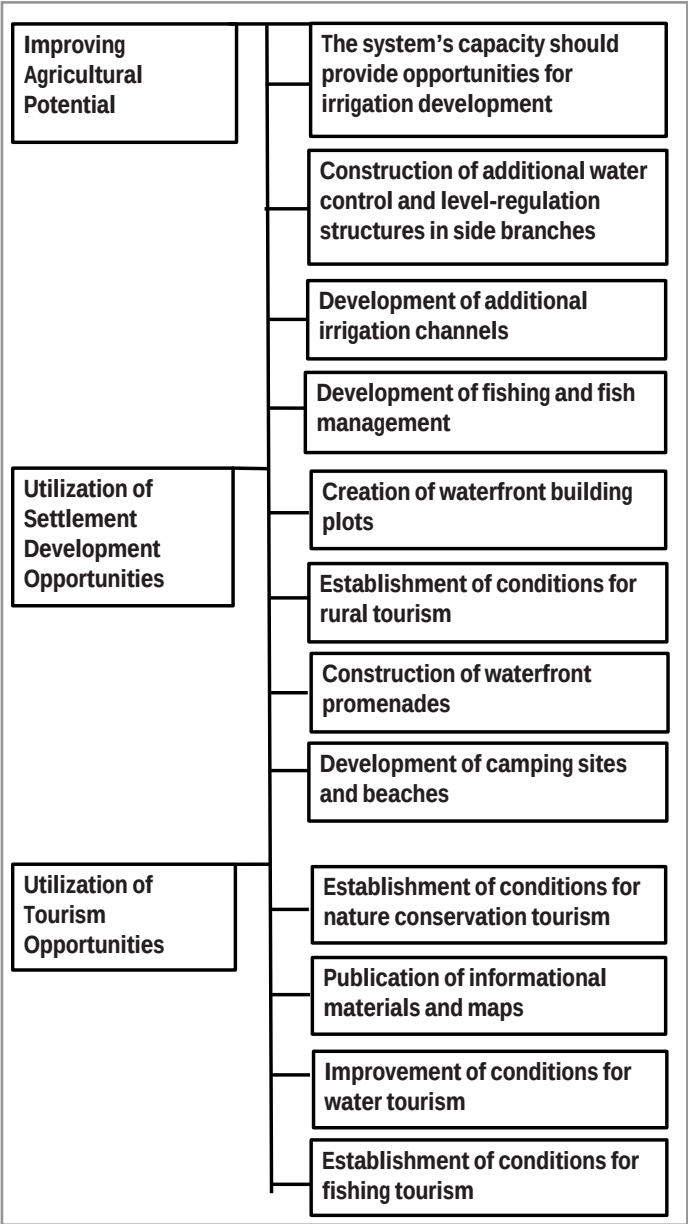


Figure 68: Function tree for secondary objectives in the historical floodplain (Dunai, 1995)

Areas suitable for water retention, such as low-lying zones and ecologically valuable wetlands, are separated from areas requiring efficient drainage by structural measures. The separation allows temporary water storage in designated zones without increasing risk in adjacent areas. System operation also plays a key role. During periods of excess water, drainage capacity is prioritized to prevent damage. Under normal or low-water conditions, water retention and redistribution become dominant functions. This dynamic mode of operation requires continuous regulation through hydraulic structures and depends on hydrological forecasting and monitoring.

5.2.2. Active floodplain

The main functional relationships in the active floodplain are summarized in Figure 70.

The map illustrates the spatial relationships among the main functional zones identified in the active floodplain function tree. The map shows how ecological restoration, water management, and human activities, such as water sports, tourism, and infrastructure, coexist within a coordinated system.

5.3. Operating regulations development

Directive 2000/60/EC, which established the Water Framework Directive (WFD), was adopted in October 2000 and entered into force in December 2000. The operating rules developed during the test operation were reviewed in light of the emerging WFD approach. For water bodies formally designated as heavily modified, the environmental objectives are good ecological potential and good surface-water chemical status. The designation of a water body as heavily modified and the application of these objectives are subject to the conditions defined in the Directive.

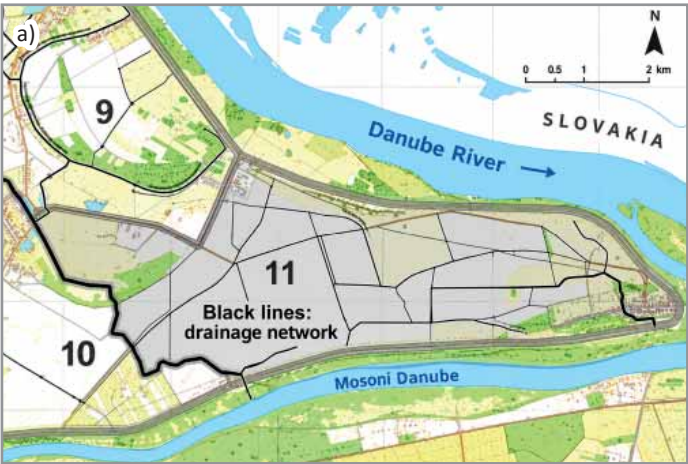


Figure 69: Examples of multifunctional water management in the historical floodplain; a) rehabilitation in Lower Szigetköz (Dunai, 2006); b) double-functioning channel in the lower historical floodplain at Kisbajcs

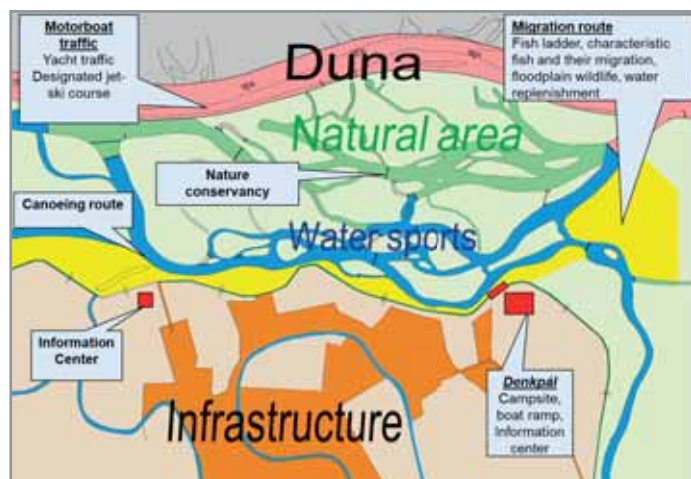
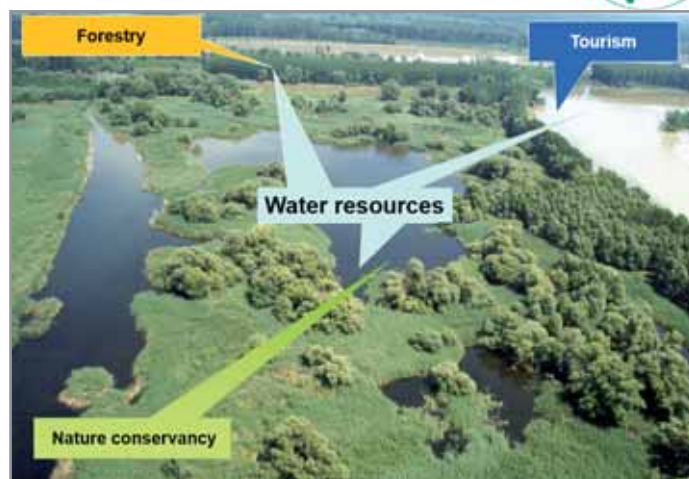


Figure 70: Functions in space and time (Janák et al., 2014)



The assessment concluded that the established replenishment system and its operating rules were consistent with measures intended to support good ecological potential. The following changes and adjustments were incorporated into the operating regulations.

5.3.1. Operating alternatives and constraints

Based on the experience gained during the test operation, experts developed an alternative operating strategy to meet agreed-upon needs while accounting for existing hydrological and morphological constraints. The principal limitations were the available discharge and the spatial extent reached by the replenishment system. The 1995 water-sharing agreement remained in effect, with a maximum normal discharge of 600 m³/s into the Old Danube and up to 150 m³/s available for the Hungarian floodplain systems. The available discharge was insufficient to reproduce natural flood conditions during normal operation. One of the initial refinements focused on improving the dynamic allocation of water at the intake to the replenishment system. Water replenishment for the Mosoni-Danube and the historical floodplain was restructured to reflect seasonal rather than daily variability.

5.3.2. Key adjustments based on flood experience

Operational experience showed that rapid increases and decreases in incoming discharge during flood periods could cause severe erosion, particularly near hydraulic structures, and could threaten the safe operation of the replenishment system. The operating rule was therefore changed from the use of a daily mean discharge to a two-day mean discharge. The longer averaging period maintained a dynamic water supply while reducing the risk of abrupt operational changes and associated erosion.

5.3.3. Integration of stakeholder input

Stakeholder input remained an important element throughout this phase, as farmers, conservationists, and water managers used monitoring data to refine water-level targets for specific areas within the floodplain, ensuring that local conditions and practical needs were reflected in operational decisions. The test operation demonstrated that this approach was both technically feasible and broadly acceptable. The consultation process continued after the 2000 permit phase, and by 2002 stakeholders had endorsed an operational strategy based on natural flow dynamics supported by clearly defined rules and procedures. It was also agreed that, even after the operating permit was issued, the water management authority would continue to provide regular reports and maintain opportunities for review, allowing the system to be reviewed and adjusted in response to changing ecological, agricultural, and hydrological conditions.

5.3.4. Dynamic and minimally involved operations

The system was designed to operate dynamically while limiting unnecessary intervention. Discharge into the active floodplain is determined based on the mean Danube discharge measured at Bratislava (Dévény) during the previous two days. In contrast, the Mosoni-Danube and the historical floodplain follow a more seasonally regulated regime. Maintenance interventions are kept to a minimum: morphological changes are monitored but generally not corrected unless they obstruct flow or pose a risk to flood protection. Similarly, natural elements such as fallen trees are removed only when they significantly impede water conveyance.

5.4. Water replenishment system operation regulation

The main provisions of the operating regulations are summarized below.

5.4.1. General description

The active and historical floodplain systems form an interconnected water-replenishment network. Water can be transferred from the active floodplain to the historical floodplain at Dunaremete and at two additional sluice-controlled connections. A further connection allows water to be transferred in the opposite direction, from the historical floodplain to the active floodplain.

The active floodplain receives water directly from the Old Danube. The submerged weir at Dunakiliti raises the upstream water level, creating the water-level difference required for gravity-fed inflow through the right-bank branch-system intakes. The Dunakiliti Barrage regulates this upstream water level and, consequently, the discharge entering the active floodplain.

The 1995 Agreement established how much water the Slovak side was to release at Čunovo into the Old Danube and toward the Mosoni-Danube system. The required releases were determined from the Danube discharge measured at Bratislava (Dévény), together with the applicable seasonal operating rules.

After entering the Hungarian section, the water was distributed through the Szigetköz replenishment system. Figure 71 shows the relationship between the discharge measured at Bratislava and the flow entering the Hungarian section at Rajka.

The active floodplain system was developed using existing branches and newly constructed connector channels. The historical floodplain system uses former riverbeds and channels that serve both water replenishment and the drainage of excess inland water.

For the section downstream of Rajka, the flow balance can be expressed as:

$$Q_{\text{Rajka}} = Q_{\text{active}} + Q_{\text{submerged weir}} + Q_{\text{Dunakiliti}}$$

where Q_{Rajka} is the flow entering the Hungarian section at Rajka, Q_{active} is the flow diverted into the active floodplain, $Q_{\text{submerged weir}}$ is the flow passing over the submerged weir, and $Q_{\text{Dunakiliti}}$ is the flow passing through the Dunakiliti Barrage.

The Szigetköz replenishment system receives water through two main routes (ÉDUVIZIG, 2000b):

1. From the Old Danube through the branch-system intakes upstream of the submerged weir, mainly supplying the active floodplain.
2. Through the Mosoni-Danube intake structure at Čunovo and the connected supply and right-bank toe-drain channels.

Under normal operating conditions, up to 150 m³/s can be directed from the Old Danube into the active floodplain through the right-bank intake structures Öregrét and Benda, provided that the discharge in the Old Danube remains below 600 m³/s. Higher flows are permitted only during flood events, in accordance with operational regulations. The remaining flow either passes through the Dunakiliti barrage or flows over the submerged weir.

The 1995 Agreement also allocated 43 m³/s to the Mosoni-Danube and the right-bank toe-drain system, subject to hydrological and technical conditions.

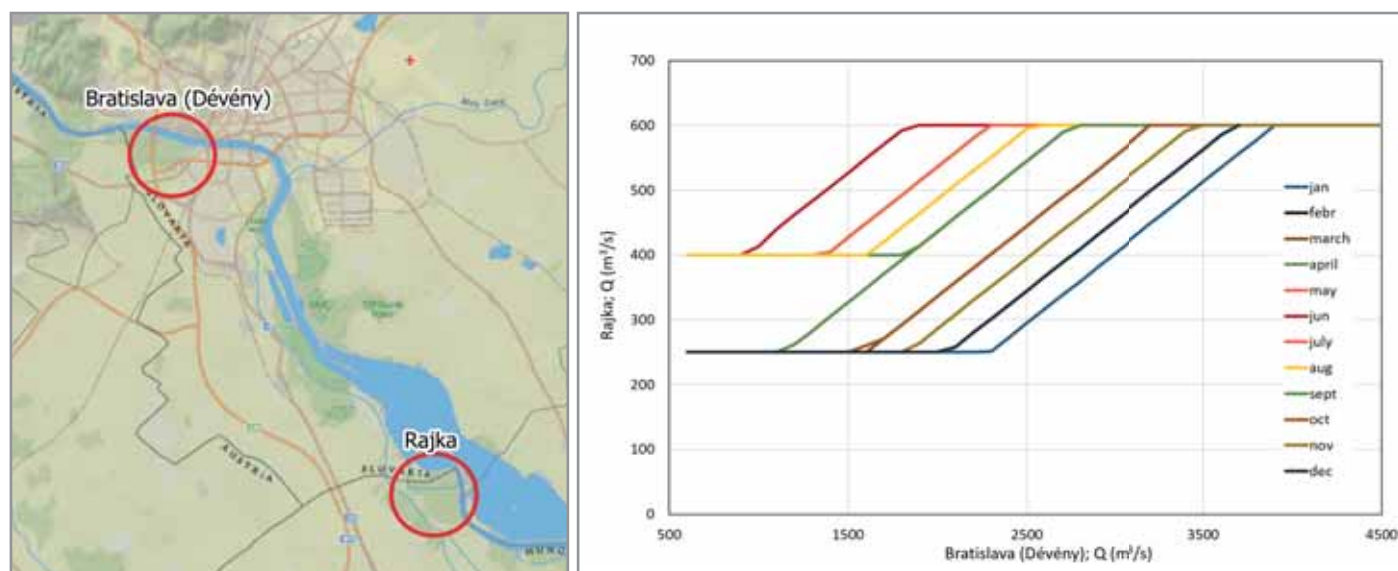


Figure 71: Relationship between the Danube discharge measured at Bratislava (Dévény) and the flow entering the Hungarian section at Rajka

On the Hungarian side, this water can be distributed through sluice gates in three directions:

1. To the Mosoni-Danube;
2. To the Zátonyi-Danube, which is the principal supply route to the historical floodplain;
3. To the active floodplain.

The layouts of the active and historical floodplain systems and the Mosoni-Danube supply route are shown in Figure 72.

Water supply to the Mosoni-Danube and the historical floodplain follows a seasonal operating schedule based on the Danube discharge measured at Bratislava (Dévény) and the time of year. The objective is to reflect seasonal changes in river flow and ecosystem water demand. Figure 73 presents the corresponding operating relationship.

The principal hydraulic structures referred to in the operating regulations are summarized in Appendix 4.

5.4.2. Operational rules

Under normal operating conditions, the extent of water replenishment is determined according to the Danube discharge measured at Bratislava (Dévény). The operating regulations distinguish between two states: normal operation and flood operation (ÉDUVIZIG, 2000).

Normal operation applies when the facilities can fully perform their intended functions, meaning that they are capable of:

- Regulating flows and water levels in accordance with the operating plan;
- Operating according to predefined procedures;
- Operating without restrictions or within predefined limits, for example during construction or maintenance work.

Nonstandard operating conditions may be either planned or unforeseen.

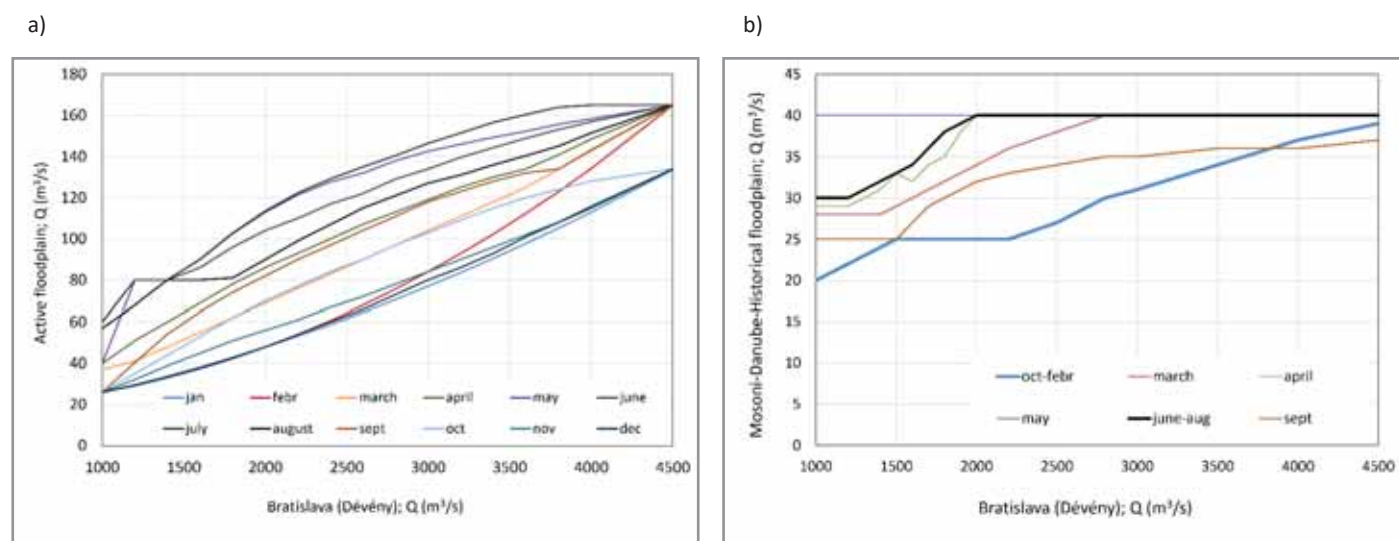


Figure 72: a) Water-replenishment systems for the active floodplain; b) the historical floodplain and the Mosoni-Danube

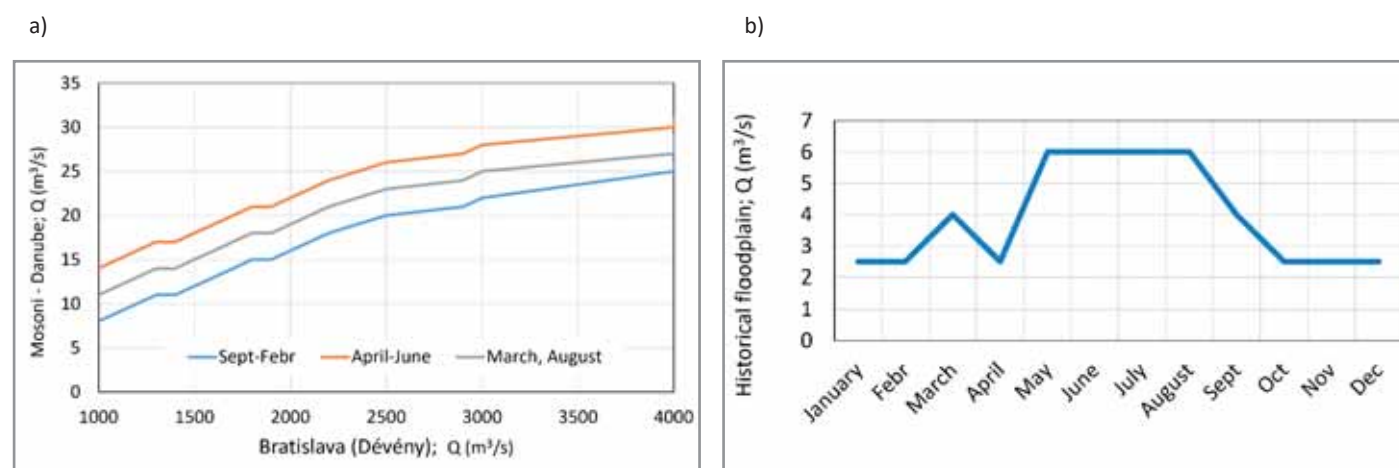


Figure 73: a) Operating relationship between the Danube discharge at Bratislava (Dévény); b) water supply to the Mosoni-Danube and the historical floodplain

Planned special operations include testing, maintenance, renovation, and controlled inundation. Unforeseen emergency operations may be required because of accidental pollution, extreme weather, structural failure, water shortages, or other events that prevent the system from operating normally. A detailed description is provided in Appendix 3.

The North-Transdanubian Water Directorate follows a predefined response plan and maintains communication with the relevant authorities during emergencies. In disaster situations, the operations center immediately informs the central flood-protection management and requests intervention if necessary.

5.4.3. Controlled floodplain inundation

Routine water replenishment restored a permanent supply to much of the branch system, but it could not reproduce the temporary rise in water levels that had formerly accompanied spring floods. After the diversion of the Danube, moderate flood waves no longer necessarily caused inundation in the Old Danube and the active floodplain. As a result, several processes associated with seasonal flooding—including fish spawning, groundwater recharge, and the renewal of floodplain vegetation—became less frequent.

Operational experience and consultation among the Water Directorate, stakeholders, and decision-makers led to the introduction of controlled floodplain inundation. The procedure was designed to recreate part of the missing spring flood pulse by temporarily increasing the discharge in the Old Danube and the active floodplain. In contrast to routine replenishment, controlled inundation raises water levels for a limited period and allows water to spread across a larger part of the floodplain.

Operating conditions

Controlled inundation may occur between April 1 and May 31, when water temperatures exceed 10 °C. The operating decision is based on the discharge measured at Bratislava (Dévény), flow forecasts, ecological conditions, and the safe operation of the hydraulic structures.

The defined operating conditions include:

- a Danube discharge of at least 3,000 m³/s at Bratislava;
- a forecast indicating flows above 2,500 m³/s for approximately 14 days;
- an increase in the discharge released to the Old Danube at Čunovo to approximately 800 m³/s;
- diversion of approximately 200–250 m³/s into the active floodplain;
- an inundation period of about two weeks.

Controlled inundation is not required when a natural flood exceeding 5,000 m³/s occurs during the designated spring period.



Figure 74: Controlled floodplain inundation in the Szigetköz active floodplain

Role in floodplain management

The operation is intended to support ecological and forestry functions that cannot be maintained solely by routine low-flow replenishment. The temporary increase in water levels can provide access to spawning and nursery habitats, improve groundwater recharge, and supply water to floodplain forests and wetlands during an ecologically important part of the year.

Controlled inundation does not fully reproduce a natural flood. Its timing, discharge, duration, and spatial extent are regulated, and the operation must remain compatible with flood protection, structure safety, and other water-management requirements. It nevertheless restores part of the seasonal variability that is otherwise missing from the regulated system.

Where operationally feasible, the discharge is reduced gradually at the end of the inundation period, allowing water levels to recede more slowly and reducing the risk that fish and juveniles become stranded in temporarily inundated areas.

Use in practice

Controlled inundation has been implemented in several years since 2004, including 2004, 2005, 2008, 2009, 2010, 2013, 2014, 2016, 2017, 2019 and 2023. Its repeated use shows that the operating system was adapted after the initial rehabilitation to address ecological needs that could not be met solely through a permanent water supply.

The Black Stork and the Szigetköz –A Delicate Bond Between Water and Forest

The Szigetköz, one of Hungary's most important floodplain ecosystems, is also one of the last strongholds of the black stork (*Ciconia nigra*) in the Little Hungarian Plain. This strictly protected species nests in quiet, undisturbed forests but depends on shallow backwaters, marshes, and wet meadows, where it feeds on fish, frogs, and aquatic insects. The mosaic landscape of the Szigetköz — its network of river branches, floodplain forests, gravel bars, and open meadows — provides ideal conditions for its survival.

After the diversion of the Danube, however, the black stork's habitats came under threat: many of its nesting areas dried out as side channels lost water and the groundwater level dropped. The construction of the water replenishment system, designed to restore the flow and vitality of the floodplain channels, has gradually brought positive change. In recent years, the species has shown signs of recovery, and several breeding pairs have been observed once again in the deeper forests of the Szigetköz. The presence of the black stork carries not only ecological but also symbolic meaning: wherever water returns, life follows. In this way, the black stork has become a living indicator species of the Szigetköz — a sign that the delicate balance between water, forest, and people is beginning to heal.

(http://kisbodak.network.hu/kepek/szigetkoz_allatvilaga/szigetkoz_fokozottan_vedett_madarai_a_fekete_golyak)



6. ESTABLISHING THE SZIGETKÖZ OPERATING COMMITTEE

Since 1993, stakeholders have been progressively involved in damage mitigation and, following test operations, the Szigetköz Operating Committee was formally established in 2001. The Committee provided a permanent forum for reviewing system performance, resolving conflicts, and recommending operational changes within the limits of the existing permit.



Figure 75: Process leading to the establishment of the Szigetköz Operating Committee.



Transferable lesson 6 — Institutionalize stakeholder participation in long-term operation

Challenge addressed

Stakeholder involvement often ends when construction is completed or the operating permit is issued. Long-term operation, however, continues to create conflicts over water levels, maintenance, ecological needs, and exceptional operating conditions.

Approach used in Szigetköz

The Szigetköz Operating Committee created a permanent forum for water managers, conservation authorities, municipalities, farmers, foresters, fishers, tourism representatives, and other water users. The Committee reviews annual operating experience, discusses requests for change, coordinates exceptional operations, and recommends amendments that remain within the existing permit.

General principle

Stakeholder participation should continue after permitting. A permanent and documented review process helps maintain trust, resolve conflicts, and adapt operation without reopening the entire planning process for every minor change.

Conditions for transfer

The committee should include the main affected sectors, meet regularly, record its decisions, and clearly distinguish between operational adjustments allowed under the existing permit and changes requiring a new permit procedure.

Suggested indicators

Meeting frequency and participation, number of operational recommendations, proportion of agreed changes implemented, unresolved conflicts, and response time to exceptional events.

Establishing the Szigetköz Operating Committee

After the construction of the first phase of the water replenishment system in 1995, the Water Directorate sought to maintain the trust established during the planning process. In 1999, following several years of test operations, stakeholders were convened again to discuss the system's long-term operation. After the operating permit was issued, the Szigetköz Operating Committee was formally established in 2001, with representatives from water management, disaster management, nature conservation, forestry, agriculture, local government, fishing, and tourism. The stakeholder-based process leading to the establishment of the Szigetköz Operating Committee is illustrated in Figure 75.

The Committee meets at least once a year to evaluate the operation of the water replenishment system and recommend measures for the following year, such as adjustments to target discharges or water levels at specific locations. The Committee also serves as a forum for resolving conflicts among water users. Operational changes may be adopted through the Committee when they remain within the limits of the existing permit. Changes that substantially alter the permitted operation require a separate permit procedure.

The rules and procedures for the Operating Committee are:

- The Water Directorate organizes the meetings and prepares the operational information required for discussion.
- The Committee meets at least once a year. Minutes are prepared and agreed decisions regarding operations and maintenance are recorded.
- Operational experience from the previous year and requests for changes are presented to the Committee. The Water Directorate then prepares proposed responses or technical solutions.
- Amendments supported unanimously may be incorporated into the operating instructions, provided that they remain within the existing permit.
- Additional meetings may be convened to address exceptional operational needs.
- The Water Directorate informs Committee members of extraordinary events and of works whose timing may affect water replenishment.
- Where the timing of permitted construction or maintenance work is not specified in the permit, the proposed implementation date is presented to the Committee for coordination.

The visible results of the water replenishment system strengthened public confidence in the project and demonstrated the value of cooperation between engineering and ecological disciplines. The Operating Committee also gave local stakeholders and the North-Transdanubian Water Directorate a more structured basis for presenting regional water-management needs and coordinating future improvements.

When Water Became a Community Matter

The construction of the Szigetköz water replenishment system affected not only the natural environment but also local communities. Following the diversion of the Danube, the drying of side channels and the decline in groundwater levels led to increasing tensions among fishermen, farmers, and conservationists. Some groups called for more water to support irrigation and fisheries, while others emphasized the protection of remaining natural habitats. In response to these conflicts, the Szigetköz Operating Committee was established in 2001, bringing together water management experts, municipalities, NGOs, and local residents.

The committee aimed to jointly plan and manage water distribution, determining when and how much water should be released into the side branches so that agricultural, fisheries, and Natura 2000 conservation needs could be balanced. This approach introduced a new level of community participation in water management. For the first time, many people in the region felt that the system was being operated with their involvement rather than independently of them.

Although negotiations were often challenging, their outcomes became visible over time. Several settlements experienced improved water availability, fishing areas were revitalized, and ecological restoration objectives were gradually achieved. The experience of the Szigetköz reshaped not only the flow of the Danube's side branches but also the nature of cooperation, demonstrating that water management and community interests are closely interconnected.



7. REHABILITATION OF THE MOSONI-DANUBE

This chapter presents the rehabilitation of the Mosoni-Danube as a coordinated project covering the entire watercourse. The project was implemented in two main phases: the section upstream of Győr and the section downstream of Győr. Although the two phases addressed different local problems, both aimed to improve water levels, ecological connectivity, flood protection, and the relationship between the river and the surrounding settlements.



Figure 76: Mosonmagyaróvár Barrage



Transferable lesson 7 — Plan rehabilitation at the scale of the whole river corridor

Challenge addressed

River problems often extend beyond individual sites. Low water levels, disconnected habitats, urban needs, navigation, and flood protection may affect different reaches of the same river and cannot be solved effectively through isolated projects.

Approach used in Szigetköz

The Mosoni-Danube rehabilitation covered the whole watercourse but was implemented in two phases. Upstream of Győr, the works focused on urban reaches, oxbows, wetlands, tributaries, and ecological passage at existing structures. Downstream and around the city of Győr, the principal issues were persistently low water levels, weak connections with the Rába and side branches, navigation, and flood protection. The two phases therefore addressed different local problems within one connected river system.

General principle

Define rehabilitation objectives for the whole river corridor, then divide implementation into manageable phases without losing the connections between them.

Conditions for transfer

The approach requires basin-scale assessment, coordination among sectors and municipalities, and project phases that share common hydraulic and ecological objectives.

Suggested indicators

Water levels, connected side branches and wetlands, length of rehabilitated river reaches, ecological passage at structures, flood-protection performance, and achievement of navigation or urban-water objectives.

Rehabilitation of the Mosoni-Danube

The Mosoni-Danube rehabilitation was a large, multi-component program covering the river, its urban reaches, side branches, wetlands, oxbows, and major hydraulic structures. The upstream phase affected all 16 settlements along the Mosoni-Danube and required water-management, ecological, landscape, urban, and recreational objectives to be considered together. The project therefore extended beyond channel reconstruction and treated the river as part of a wider ecological and social landscape. The Mosonmagyaróvár Barrage, one of the principal structures included in the upstream rehabilitation phase, is shown in Figure 76.

The rehabilitation effort covered the entire Mosoni-Danube watercourse. For planning and permitting purposes, the project was divided into two sections. Implementation was then carried out in two distinct phases: the first covered the reach upstream of Győr, and the second, the reach downstream of Győr.

7.1. Upstream from Győr – design and construction of the first phase (completed in 2015)

This phase addressed the adverse effects of earlier river regulation, such as riverbed incision and the separation of aquatic habitats caused by levees and sluice gates. Key elements of the project included (Dunai, 2024):

- Urban water-management and infrastructure improvements;
- Ecological rehabilitation of the Mosoni-Danube, including:
 - restoration of water supply to oxbows and wetlands;
 - improvement of longitudinal connectivity at the Mosonmagyaróvár Barrage for aquatic organisms and water-based recreation;
- Rehabilitation of the lower section of the Lajta River;
- Reconstruction of the intake sluice supplying the Püspökerdő oxbow lake.

The scale of the first phase was unusually broad. The works included approximately 29 km of urban river reaches, four oxbows, five wetlands, and the side branches of 15 islands over a combined length of about 35 km. The lower 4 km of the Lajta River were also reconstructed, together with the Mosonmagyaróvár barrages on the Mosoni-Danube and the Lajta. The interventions therefore combined channel rehabilitation, habitat reconnection, flood conveyance, urban waterfront improvements, and the modernization of hydraulic structures. Continuous water replenishment had improved the general water supply, but it also exposed problems that had developed during earlier low-water decades.

Vegetation had narrowed some channel sections, fallen trees and accumulated driftwood obstructed flow, and sedimentation accelerated the separation of less-defined side branches. Other branches, tributaries, and drainage channels were gradually losing their connection with the Mosoni-Danube, with adverse consequences for water quality and ecological passage. The interventions restored water supply and connectivity in several disconnected or poorly supplied water bodies and combined ecological rehabilitation with urban water-management improvements (Figure 77).

The Mosonmagyaróvár Barrage and the related Lajta River structures are shown in Figure 78. The barrage forms a key control point within the upstream rehabilitation system, where water-level regulation was combined with improved longitudinal connectivity. The associated Lajta structures formed part of the rehabilitation of the lower Lajta River and the upstream Mosoni-Danube project (Dunai, 2024).

Figure 78 illustrates how several functions were combined within the same rehabilitation sites. At the Mosonmagyaróvár Barrage, water-level regulation was accompanied by facilities for fish movement and water-based recreation, including a fish passage, resting areas, and a boat chute. The reconstruction of the Lajta Barrage also addressed structural and flood-safety problems while adding a fish passage on the left bank. These measures show that longitudinal connectivity was incorporated into the reconstruction of existing water-control structures rather than treated as a separate intervention.

7.2. Downstream of Győr – second phase (2017–2022)

The downstream section presented greater challenges because of persistently low water levels. After extensive consultation, the Mosoni-Danube Outflow Structure was constructed near the confluence with the Danube, as shown in Figure 80. The structure was designed to address the persistently low water levels and weakened hydraulic connections that had developed in the lower Mosoni-Danube and the adjoining Rába system. Key objectives included:

- Restoring water levels in the Mosoni-Danube and Rába rivers to conditions approximating those of the 1950s;
- Re-establishing connections with side branches and historical floodplain branches, and enhancing groundwater recharge;
- Improving navigation conditions on the Mosoni-Danube, with the long-term objective of supporting a Class IV waterway;
- Providing flood protection for Győr and the surrounding areas.

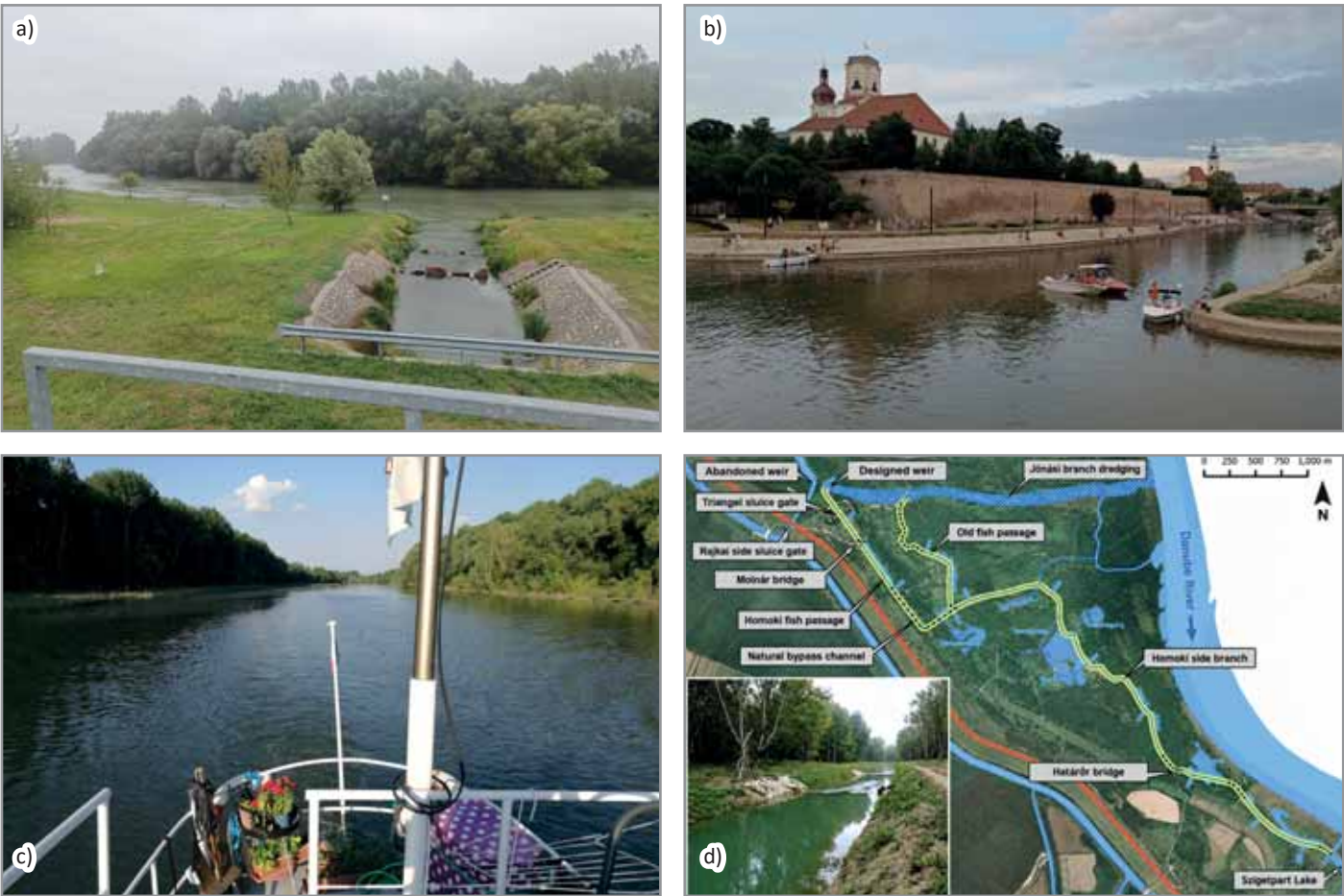


Figure 77: Rehabilitation of the Mosoni-Danube: (a) Historical floodplain branch connection into the Mosoni Danube upstream from Győr (b) River landscape in Győr; (c) small boat downstream from Győr; and (d) oxbow rehabilitation (Dunai, 2024)



Figure 78: Mosonmagyaróvár Barrage (b, c) and its surroundings on the Mosoni-Danube, and the Lajta control structure and fish passage (d)(Bencze, 2017)

The contrast shown in Figure 79 illustrates the water-level problem that shaped the downstream rehabilitation. Before construction of the outflow structure, low water levels reduced water depth and weakened the hydraulic connection between the Mosoni-Danube, the Rába, and adjoining side branches. The new structure was designed to raise and regulate upstream water levels, creating more favorable conditions for branch connectivity, navigation, and the urban waterfront in Győr.



Figure 79: Water levels in Győr before and after construction of the Mosoni-Danube Outflow Structure



Figure 80: (a, b, c) Mosoni-Danube outflow structure near Győr, DALIA project group picture at outflow structure

“Vizet a Dunába!”

On the 20th anniversary of the Danube diversion in 2012, local residents, experts, and environmental organizations gathered in Dunakiliti to draw attention to the water management problems of the Szigetköz. The event was connected to the national “Vizet a Dunába!” (Water into the Danube) initiative, launched by the Kisalföld newspaper, which called for parliamentary discussion on restoring water supply in the Old Danube and the Mosoni-Danube. The petition gained strong public support, with more than 80,000 signatures, reflecting widespread concern about the ecological and hydrological state of the region. The movement emphasized that, despite improvements from the replenishment system, significant issues remained, particularly in the Lower Szigetköz and the Old Danube channel. The demonstration and accompanying actions symbolized both public awareness and continued demand for long-term, sustainable solutions to restore river connectivity and water levels.

7.3. Main results

The rehabilitation of the Mosoni-Danube demonstrates an integrated approach to water management, combining ecological restoration with urban water management, flood protection, navigation, and other social and economic functions. The upstream phase focused mainly on urban river rehabilitation, oxbows, tributary reaches, and ecological connectivity. The downstream phase addressed persistently low water levels and weakened connections between the Mosoni-Danube, the Rába, side branches, and adjoining floodplain areas.

Together, the two phases improved water-level control and restored connections in several parts of the river system. The two phases were planned through coordinated consultation because ecological restoration, flood protection, navigation, and urban water-management objectives affected the same river corridor.

8. REHABILITATION OF LOWER SZIGETKÖZ

This chapter describes the extension of water replenishment to Lower Szigetköz. The intervention addressed the progressive loss of flow in the lower floodplain branches, extended water supply to the historical floodplain, and incorporated fish passages and other structures intended to improve ecological connectivity. The main objective was not to introduce substantially more water into the system, but to retain and redistribute the available replenishment flow so that it could reach branches farther downstream.

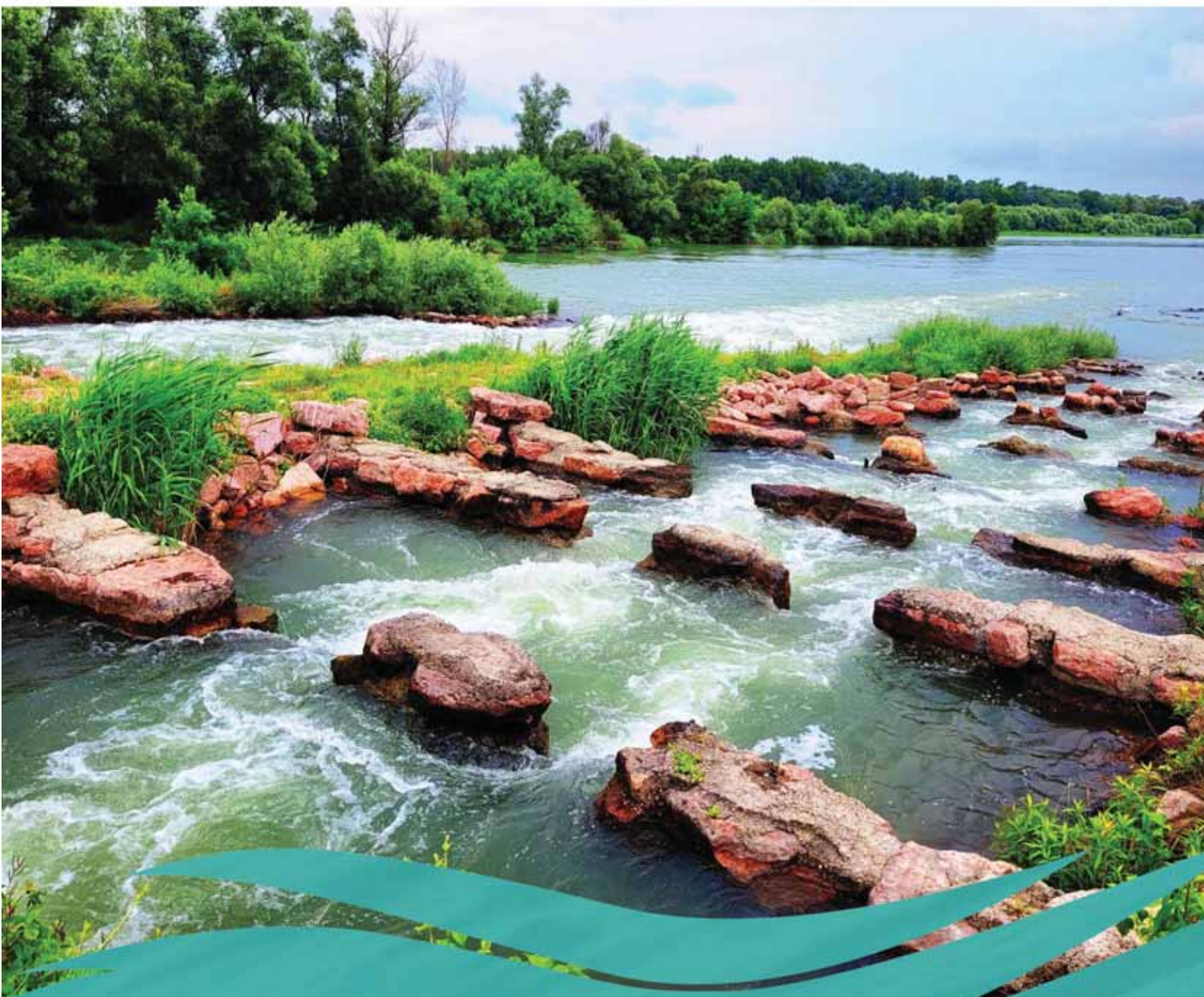


Figure 81: Ásványráró fish passage



Transferable lesson 8 — Extend existing systems by retaining and redistributing available water

Challenge addressed

Some floodplain areas may remain dry even after a replenishment system has been constructed. Additional water may be limited or unavailable, while new closures and control structures can create barriers to aquatic movement.

Approach used in Szigetköz

In Lower Szigetköz, water that had previously returned from the Ásványi system to the Old Danube was retained and directed farther downstream through the lower Ásványi, Bagaméri, and Patkányosi branch systems. The historical-floodplain drainage network was reconstructed to support drainage, water retention, habitat supply, and water distribution. Fish passages were incorporated at new submerged weirs, while siphons were built to transfer water to the historical floodplain.

General principle

Before seeking a new water source, determine whether existing flows can be retained, redistributed, and connected to areas that remain poorly supplied.

Conditions for transfer

The system must have sufficient available flow, controllable connections, suitable channel capacity, and structures that preserve drainage and flood-safety functions. Barriers created by water-level regulation should be addressed through fish passages or alternative routes.

Suggested indicators

Water delivered to previously unsupplied branches, duration of channel flow, wetland water supply, groundwater response, operation of drainage and retention functions, and continuity for aquatic organisms.

Rehabilitation of Lower Szigetköz

8.1. Hydrological and morphological problems

Since 1995, significant new water-management problems have emerged in Lower Szigetköz. During low-water periods, several floodplain branches periodically dried out, while the area of wetland habitats gradually declined. Hydrological studies identified substantial riverbed deepening along the Danube downstream of rkm 1811. As the riverbed and low-water levels declined, water entered the adjoining side branches less frequently and, in some cases, flow ceased completely.

The diversion of the Danube also had indirect effects farther downstream. Water levels decreased in the lower Ásványi branch system and in the Bagaméri and Patkányosi systems, accelerating the aging of these channels and their gradual loss of aquatic character. Photographs presented by Kertész show nearly dry sections of the Bagaméri branch system in August 2003, illustrating the severity of the low-water conditions before the later rehabilitation works (Kertész, 2017).

Downstream of the Gabčíkovo Hydropower Plant tailrace near Szap, the water returning to the Danube carries little coarse bedload. The remaining finer sediment is insufficient to maintain the river's sediment balance, and the flow therefore erodes material from the channel bed. Monitoring between Szap and Gönyű recorded channel deepening and a negative sediment balance, particularly upstream of the Medve bridge. Farther downstream, erosion and deposition occurred in alternating reaches. Floodplain sedimentation also contributed to the gradual weakening of connections between the main channel and the branch systems (Kertész, 2017).

The problems were not limited to the active floodplain. A 2006 planning assessment found that several channels outside the existing historical-floodplain replenishment system remained dry. Valuable wet meadows in the upper part of the Szavai drainage basin also dried out during low-water periods. Groundwater levels were declining in parts of Lower Szigetköz because of lower low- and medium-water stages in the Danube and the drawdown associated with groundwater abstraction (Dunai, 2006).

The rehabilitation therefore had to address several connected problems: declining river and groundwater levels, reduced inflow to floodplain branches, sediment-related channel changes, wetland drying, and the continuing need to drain harmful excess inland water.

8.2. Extension of water replenishment in the active floodplain

The ecological development project was completed in 2015. Before its implementation, the active-floodplain replenishment system extended only to the upper end of the Ásványi branch system. The lower Ásványi branches and the Bagaméri and Patkányosi systems remained outside the regularly supplied area.

The project used water from the existing Upper Szigetköz replenishment system that had previously passed through the Ásványi branch and returned to the Old Danube. The main task was therefore not to increase the total amount of water entering the active floodplain, but to retain part of the existing flow and direct it farther downstream (Kertész, 2017).

In the Ásványi system, the works included construction of the Ásványi outlet submerged weir with a fish passage, connection of the lower branch system, and dredging of the Béka-ér feeder channel. The structure raised the upstream water level and improved water transfer into the lower branches, while the fish passage reduced the barrier created by the water-level difference. The fish passage at Ásványráró is shown in Figure 81.

Water then continued from the lower Ásványi system into the Bagaméri branch system through the modified Árvai closure. The works included dredging the Bagaméri main branch, restoring the water supply to Árvai Lake, modifying several existing closures, and constructing the Bagaméri outlet submerged weir near rkm 1809.7. This structure also included a fish passage (Kertész, 2017).

The Patkányosi system received most of its replenishment water from the Bagaméri system. Its rehabilitation included dredging of branches and feeder channels, and the construction or modification of several low-control structures. The interventions created a continuous downstream sequence: water was retained in the lower Ásványi system, passed into the Bagaméri branches, and then supplied the Patkányosi system.

Figure 82 shows the arrangement of the three lower branch systems and the main direction of water transfer.

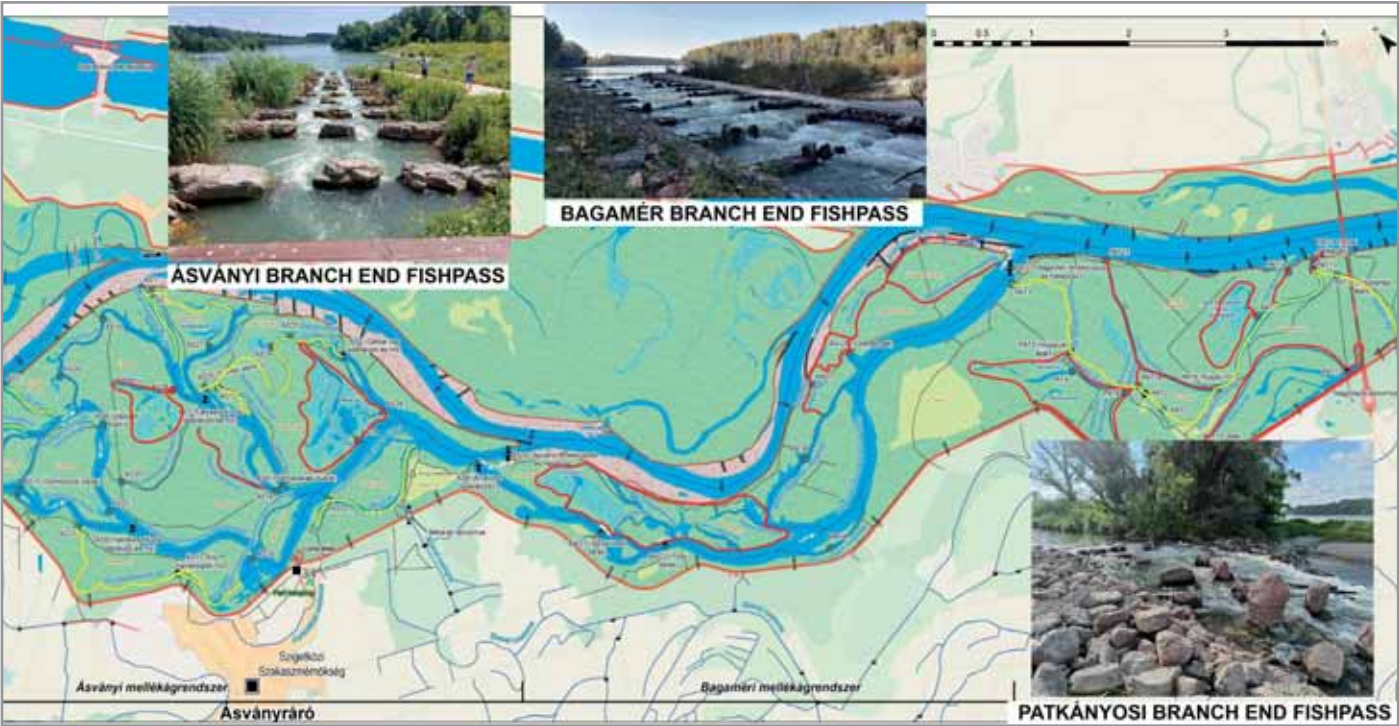


Figure 82: Extension of water replenishment through the lower Ásványi, Bagaméri, and Patkányosi branch systems with photos of fish passages (source of base map: ÉDUVIZIG)

8.3. Historical floodplain water supply and ecological connectivity

Improved water supply in the active floodplain also created new opportunities to supply the adjoining historical floodplain. Three siphon-based intake points serve the protected-side system:

- the Béka-ér siphon at Ásványráró;
- the Patkányosi siphon;
- the Nagybjacs siphon.

The Patkányosi siphon had previously operated only intermittently, when Danube water levels were sufficiently high. Improved water supply in the active-floodplain branches allowed the Patkányosi intake and the newly constructed Béka-ér and Nagybjacs siphons to operate under a wider range of conditions (Dunai, 2006; Kertész, 2017).

Figure 83 shows the Béka-ér siphon, one of the structures used to transfer water within the system.

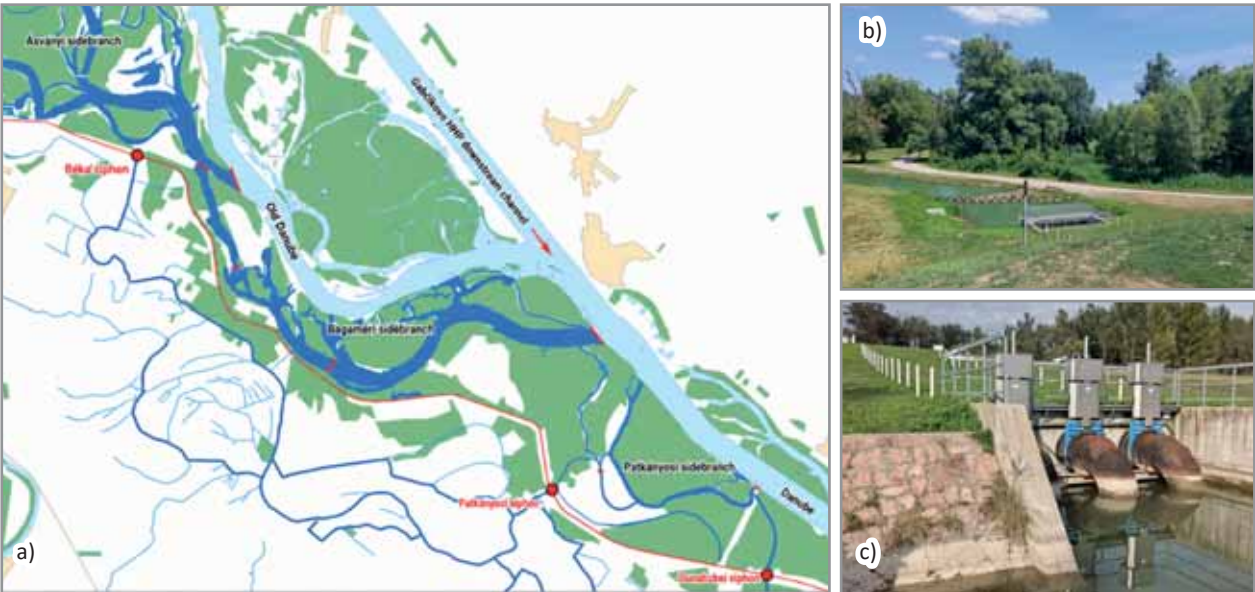


Figure 83: a) Lower active and historical floodplain (Kertész J., 2017); b, c) Béka-ér siphon in Ásványráró supplying water from the a) active floodplain to the historical floodplain

The historical-floodplain drainage network was reconstructed in parallel with the extension of the active-floodplain system. New and modified structures enabled control of water levels and flow directions. The same channel network could therefore continue to remove harmful excess water while also supplying side channels, wet meadows, and other valuable habitats.

The rehabilitation did not replace the original drainage function. Instead, it transformed the network into a multipurpose system in which drainage, water retention, and water replenishment could be emphasized under different hydrological conditions. The planning documents retained the safe removal of excess inland water as a basic function, while also including the restoration of landscape values and wetland habitats, irrigation-water supply, and improved conditions for fisheries (Dunai, 2006).

The rehabilitation of the historical floodplain network is illustrated in Figure 84.

The connected channel network also supported the development of blue corridors. These are aquatic routes that connect individual subcatchments, the historical-floodplain system, and the Mosoni-Danube. Their function depends not only on the physical continuity of the channels, but also on suitable water levels and the operation of sluices and other control structures.

Fish passages at the Ásványi and Bagaméri submerged weirs reduced the barrier effect of the new water-level-control structures within the active floodplain. Connections with the Mosoni-Danube remained equally important because siphons transfer water but do not provide a migration route for aquatic organisms. Maintaining ecological connectivity therefore required a combination of connected channels, suitable operating rules, and fish passages at structures where differences in water level could obstruct movement.

Examples of fish passages incorporated into the Lower Szigetköz system are shown in Figure 85.

Together, the measures extended regular water replenishment through the lower active floodplain and created additional supply routes to the historical floodplain. The project combined the redistribution of existing water, channel rehabilitation, water-level regulation, drainage, wetland supply, and aquatic connectivity into a single interconnected system.

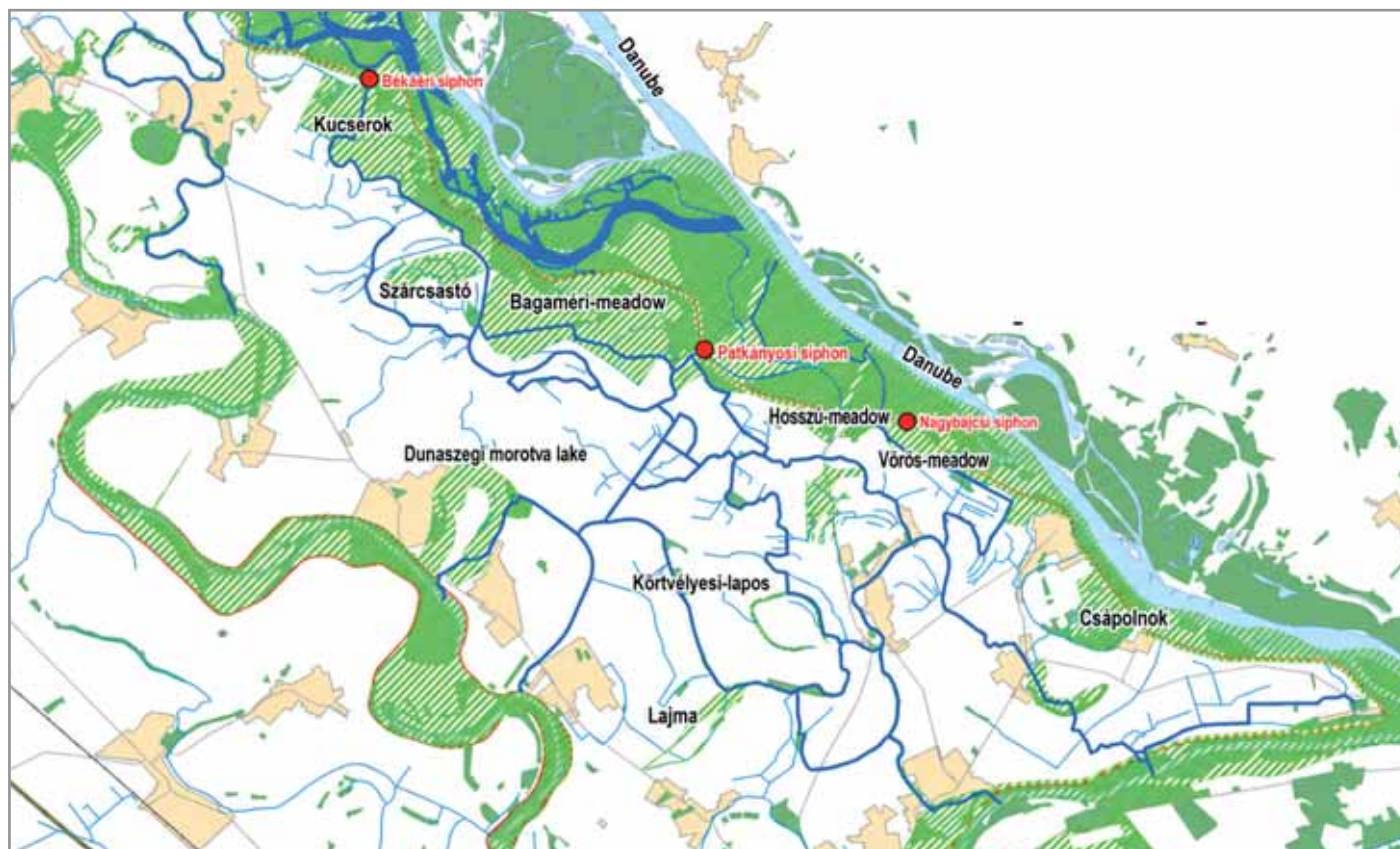


Figure 84: Rehabilitation of the multipurpose water-management network in the historical floodplain of Lower Szigetköz (Kertész, 2017).



Figure 85: Fish passages in lower Szigetköz; a) Zsejkei, b) Szavai, c) Zámolyi, d) Dunaszegi (Dunai, 2024)

SUMMARY

This book presented the historical transformation and rehabilitation of Szigetköz, a distinctive inland delta of the Danube characterized by a formerly dynamic, multi-branch floodplain system. The interaction between the main river, side branches, wetlands, and groundwater supported high biodiversity and provided important services for local communities, including water supply, agriculture, forestry, fisheries, flood regulation, and recreation.

Successive human interventions gradually changed this system. River-regulation works, flood-protection levees, channel stabilization, and drainage networks improved navigation, flood safety, and land use, but also reduced lateral connectivity and altered sediment transport. By the twentieth century, the formerly extensive floodplain had been divided into active and historical floodplain compartments, and many branches had already become less directly connected to the Danube.

The most abrupt change occurred in 1992, when approximately 80% of the Danube's discharge was diverted into the Gabčíkovo power canal. Discharge and water levels declined sharply in the Old Danube, reversing or weakening its former interaction with groundwater in the most affected areas. Groundwater levels fell substantially, many branches in Upper Szigetköz dried out, and aquatic and wetland habitats were severely reduced. Agriculture and forestry were also affected by declining groundwater and soil moisture. Lower Szigetköz was initially less affected, but its condition subsequently deteriorated as riverbed incision lowered water levels and reduced inflow to downstream branches.

Hungary responded first through emergency measures and later through the development of an extensive water-replenishment system. The system uses existing branches, newly constructed connector channels, weirs, closures, sluice gates, and gravity-fed intakes to distribute water through the active and historical floodplains and toward the Mosoni-Danube. Its objective was not to recreate an undisturbed natural river system, but to mitigate damage, restore water to dried branches, maintain selected ecological functions, and support the continued social and economic use of the landscape.

Test operation between 1995 and 2000 played a central role in refining the system. Field measurements revealed differences between planned and actual water levels, seasonal water losses, uneven hydraulic resistance, and limits in the amount of water that could be distributed through the branches.

Hydraulic modeling and monitoring were used to adjust structures and develop separate summer and winter operating parameters. The experience demonstrated that permanent operating rules could not be based solely on design calculations; they had to be developed gradually from measured performance under different hydrological and seasonal conditions.

The operating regulations also had to balance several sometimes conflicting functions. Flood protection, water supply, ecological restoration, agriculture, forestry, fisheries, tourism, and drainage required different water levels, flow conditions, and operating periods. Value analysis and function trees were used to make these needs and conflicts explicit. Some functions were separated in space or time, while others were reconciled through operating limits, technical measures, or agreed compromises.



Figure 86: Denkpál fish passage connecting the floodplain river branches and the Old Danube

Stakeholder participation continued after the operating permit was issued. The Szigetköz Operating Committee, established in 2001, provided a permanent forum for reviewing annual operating experience, discussing requests for changes, resolving conflicts, and recommending adjustments within the limits of the permit. Monitoring data and hydraulic analyses supported this process, allowing operating practices to be reviewed as environmental conditions and local needs changed.

The rehabilitation continued after the initial system was completed. Controlled floodplain inundation was introduced to restore part of the spring flood pulse that routine replenishment could not provide. The Mosoni-Danube was rehabilitated through two coordinated project phases addressing urban river reaches, oxbows, wetlands, tributaries, low water levels, navigation, flood protection, and hydraulic connectivity. In Lower Szigetköz, existing replenishment water was retained and redistributed through the lower Ásványi, Bagaméri, and Patkányosi branch systems. The historical-floodplain drainage network was also reconstructed as a multipurpose system supporting drainage, water retention, wetland supply, and ecological connections. Fish passages were incorporated where new water-level-control structures would otherwise have created barriers. The first one of these fish passages was built in 1995. – see Figure 86.

Long-term monitoring shows substantial but uneven improvement. Water replenishment restored or stabilized surface-water conditions in many branches and supported groundwater recovery near directly supplied channels.

The quality of the Danube water entering the system also improved compared with the more polluted conditions of earlier decades. Rewatered branches, oxbows, and wetlands again supported aquatic vegetation, fish, amphibians, waterfowl, and floodplain habitats. Long-term assessments show that groundwater recovery has remained spatially and seasonally uneven. During spring and summer, groundwater levels in parts of central Szigetköz increased by approximately 20–30 cm, compensating for a substantial part of the earlier decline. Winter groundwater levels, however, continued to decrease in some upstream areas over the longer observation period (Chappon et al., 2024a).

The contrasting seasonal trends show that improved groundwater conditions during the growing season do not necessarily indicate full hydrological recovery. The reduced stage of the Old Danube and the weaker winter recharge remain important constraints in the upstream part of Szigetköz.

The recovery remains incomplete. Natural flood pulses are weaker, seasonal water-level variability is reduced, and full lateral and longitudinal connectivity has not been restored. Slow-flowing or stagnant branches remain vulnerable to sediment accumulation, fluctuations in oxygen levels, algal growth, and temporary eutrophic conditions. Groundwater recovery varies by location and season, while the reduced stage and continuing incision of the Old Danube remain major constraints. Local structures and water redistribution can mitigate these effects, but they cannot by themselves restore the sediment balance and hydrological dynamics of the entire river.

The Szigetköz experience therefore illustrates both the possibilities and limitations of rehabilitating a heavily modified river system. Its principal achievement lies not in returning the landscape to a historical natural state, but in developing an adaptable system that combines engineering, ecological knowledge, monitoring, stakeholder participation, and gradual operational refinement. Future management will need to continue this approach by addressing groundwater recharge, sediment processes, controlled inundation, water quality, fish passage, wider floodplain connectivity, and increasing climatic pressures. The long-term objective should be to improve ecological functions and ecosystem services while maintaining flood safety and the region's social and economic uses.

The eight transferable lessons derived from the Szigetköz experience do not constitute a universal design model. Their relevance elsewhere depends on local hydrology, sediment conditions, ecological objectives, available water, governance arrangements, stakeholder relationships, and the capacity for long-term monitoring and adaptive operation.

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1	Danube River at Dunaremete		Photo: Máté Chappon.
2	Location of Szigetköz along the Rhine-Main-Danube waterway	https://www.realzoldek.hu/modules.php?name=News&file=article&sid=1180	Source: realzoldek.hu.
3	An Overview Map of the Szigetköz Area. The ESRI basemap was supplemented with project geospatial data processed in QGIS		Map: Klaudia Madarász.
4	Spatially Separated Water Bodies in The Szigetköz-Csallóköz (Žitný Ostrov) Area		Map: Klaudia Madarász.
5	Examples of land use and water-related recreation in Szigetköz		Photos: Máté Chappon.
6	Workforce distribution		Source: Insula Magna Project (2022); graphic: Klaudia Madarász.
7	Depths of the Pannonian Basin, showing the deepest basin in the Danube-HLP region (Rman et al., 2021)	https://repository.europe-geology.eu/egdidocs/geoconnect3d/geoconnect3d_d52d_lessons+learnt+pannonian+basin.pdf	Source: Rman et al. (2021).
8	(a) Location of the Hungarian Little Plain in the Eastern Alps–Western Carpathians–Pannonian Basin junction area (TR: Transdanubian Range, VB: Vienna Basin). (b) Map of the HLP with thickness of the Late Miocene to Quaternary succession (Sztanó et al., 2016). Thickness data modified from Atzenhofer et al. (2011). The reconstructed prograding shelf edge—the former sedimentary margin that advanced gradually into Lake Pannon—is based on Magyar et al. (2013).	https://www.researchgate.net/figure/a-Location-of-the-Danube-Kisalföld-Basin-DKB-in-the-Eastern-Alps-Western_fig4_311974185	Source: Sztanó et al. (2016); thickness data from Atzenhofer et al. (2011); shelf-edge reconstruction based on Magyar et al. (2013).
9	Depth of Quaternary sediments below Szigetköz. The surface represents the base of the sediment layer		Graphic: Richard P. Ray.
10	Generalized soil-texture distribution in Szigetköz. Source: Agrotopographic Database (AGROTOPO), based on data from the Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences (2009)		Data source: AGROTOPO (2009); map: Klaudia Madarász.
11	(a) Surface expression of former channel-cutting and depositional patterns in agricultural fields; the image has been sharpened to emphasize the features. (b) Electrical-resistivity profile on the landward side of a flood-protection levee, showing comparable former channel features in cross-section		Images and interpretation: Richard P. Ray.
12	Longitudinal profile of the Danube showing the major regional change in channel gradient near river kilometer 1950 and the lower-gradient reach toward Szigetköz	https://www.icpdr.org/main/sites/default/files/JDS%2005%20Chapt%203.pdf	Data source: ICPDR (2005); graphic: Klaudia Madarász.
13	Median monthly discharges of the Danube at Bratislava by calendar month		Analysis and graphic: Máté Chappon; hydrological data: ÉDUVIZIG.

Fig. No.	Figure name	Link	Photo / figure credit
14	Temperature and Precipitation anomalies in Northwestern Hungary		Data source: Hungarian Meteorological Service Open Data Portal (odp.met.hu); graphic prepared using Flourish.
15	Summary of the climate risks for the 29 climate dimensions within the four categories “temperature,” “wind,” “water,” and “solid matter” for the location DPS1 (Hungary) for 2015 to 2034 (current) and 2031-2050(future) with SSP5-8.5 and RCP8.5 emission scenario (where available; discrepancies mentioned in the respective climate dimension subchapters). Only higher risk classes from current and future risks are shown in this table	https://content.meteoblue.com/assets/pdfs/ams_posters/meteoblue_AMS2025_POSTER_CRA.pdf	Source: Meteoblue (2024); adapted from the Meteoblue AMS 2025 poster.
16	Farming around 1935	https://digitaltmuseum.se/0210111393610/ungersk-graboskap-i-byn-nagy-bajcs-tjeckoslovakien-ungern-osterrike-193	Archive photograph, c. 1935. Photo/source: Facebook: Szigetköz régen és most
17	Floodplain near Ásványráró in 1965 and 1993	fentrol.hu	Source: fentrol.hu (Lechner Knowledge Center), aerial photographs from 1965 and 1993.
18	Floodplain of the Mosoni-Danube near Dunaszeg in 1965 and 1993	fentrol.hu	Source: fentrol.hu (Lechner Knowledge Center), aerial photographs from 1965 and 1993.
19	Szigetköz land use		Map: Klaudia Madarász.
20	Flora and fauna of Szigetköz: (a) wet meadow; (b) floodplain branch with reeds and forest; (c) fox in floodplain vegetation; (d) great egret in the active floodplain branch system.		Photos: (a,b) József Kertész, (c) Richard P. Ray (d) Gergely Ámon.
21	Natura 2000 protected areas		Map: Klaudia Madarász.
22	The whole floodplain is now under Natura 2000 protection		Source: Fertő–Hanság National Park Directorate.
23	Both agricultural and floodplain areas are protected	https://www.facebook.com/groups/csoalatosmagyarorszag.hu	Photos: (a) Klaudia Madarász; (b) Gergely Ámon
24	Cultural heritage in Szigetköz: (a) Hédervár Castle and (b) The oldest English oak in Hungary; (c)Traditional Ovens of Kisbodak; (d) Patkányos Pump Station and Siphon	https://www.kisalfold.hu/helyi-kozelet/2022/10/az-eleteto-vizet-adja-vedelmet-biztosit-a-szigetkoznek-a-gyorzamolyi-szivattyuhaz-fotok-video	Photos: (a)Richard Ray; (b) Klaudia Madarász; (c) József Kertész; (d) Kisalföld video
25	Tejfalusi branch system (Dunai 2024)		Source: Dunai (2024).
26	Timeline of the most significant anthropogenic alterations in the Szigetköz floodplain area between 1700 and 2023		Source: Chappon et al. (2024b).
27	Extent of regularly flooded areas along the Szigetköz reach before large-scale river regulation, reconstructed from the First Military Survey conducted between 1763 and 1785. (SEA, 2010), based on material from the collection of the Danube Museum		Source: SEA (2010), based on material from the Danube Museum collection.

Fig. No.	Figure name	Link	Photo / figure credit
28	Water level and morphological changes until 1959		Graphic: Klaudia Madarász.
29	Water level and morphological changes after 1959		Graphic: Klaudia Madarász.
30	(a) Design Concepts and Plans: Photograph of a 3-dimensional raised relief map of the impacted area of the Gabčíkovo–Nagymaros Barrage Project; (b) Axonometric computer drawing of Gabčíkovo HPP; (c) Artistic representation of the Nagymaros Barrage	(b) https://projectglobal.nl/Gabcikovo-Nagymaros-Dams (c) https://www.klimarealista.hu/bos-nagymaros-tortenete/	Source: (a) ÉDUVIZIG archive; (b), (c) website.
31	(a, b) „C” variant; (c) Čunovo Diversion Dam; (d) Dunakiliti Barrage; (e) Gabčíkovo HPP		(a) ÉDUVIZIG archive (b) Graphic: Richard Ray; Photos: (c)-(e) ÉDUVIZIG archive
32	Hydrological impact of the Danube diversion in the Szigetköz between 1992 and 1993.		Graphic: József Kertész and Klaudia Madarász.
33	Summary of the Szigetköz Danube Changes and Their Impacts		Graphic: generated by AI based on outline
34	The upstream reach of the Mosoni-Danube at the Mosonmagyaróvár barrage		Photo: Gergely Ámon.
35	Flows in the supply channel and toe drain towards the Mosoni Danube		Graphic: Klaudia Madarász.
36	Flow in the supply channel and toe drain at the Rajka sluice gate		Photo: ÉDUVIZIG archive; Graphic: Klaudia Madarász.
37	Starting point of the Historical floodplain branch system (left). The connection between the toe-drain and the historical floodplain branch system was established as an emergency measure during 1993 (right).		Photos: Máté Chappon.
38	Dry conditions in the Zátonyi-Danube near Doborgazsziget in November 1992.		Photo: József Kertész.
39	The Zátonyi-Danube near Doborgazsziget after the return of water in May 1993.		Photo: József Kertész.
40	(a-b) Dry active floodplain branches following the diversion of the Danube.		Photos: (a) Fertő–Hanság National Park Directorate, (b) József Kertész.
41	Connection between the toe-drain channel and the Zátonyi-Danube		Photo: Máté Chappon.
42	The replenished Zátonyi-Danube in the historical floodplain water-replenishment system.		Photo: Máté Chappon.
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44	Rating curve based on Danube discharge at Bratislava (Dévény) and the corresponding river stage at Dunaremete during 1950–1959 and 1989–1992		Analysis and graphic: Katalin Bene; data: ÉDUVIZIG.
45	Changes in daily water levels between 1950 and 1959 in Dunaremete		Analysis and graphic: Katalin Bene; data: ÉDUVIZIG.

Fig. No.	Figure name	Link	Photo / figure credit
46	Monthly min, mean, and maximum water levels at Dunaremete during 1950–1959		Analysis and graphic: Katalin Bene; data: ÉDUVIZIG.
47	a) Dynamic control of the active floodplain; b) overflow weirs to supply the active floodplain; c) submerged weir, and Dunakiliti Barrage		Graphic: Klaudia Madarász, Satellite image: maps.google.com Photo: ÉDIVIZIG archive
48	Construction of the submerged weir I		Photo: József Kertész.
49	Construction of the submerged weir II		Photo: József Kertész.
50	Construction of the submerged weir III		Photo: József Kertész.
51	Operation of the submerged weir		Photo: József Kertész.
52	The Dunakiliti Barrage and (b) submerged weir raised upstream water levels, enabling inflow into the active floodplain branch system		Photos: (a) Richard Ray (b) Máté Chappon
53	Hydraulic control of the Danube and its floodplain systems between Čunovo and Vámoszabadi. From north to south, the figure shows the Gabčíkovo supply canal, the Slovak active floodplain branches, the Old Danube, the Hungarian active floodplain branches, and the Hungarian historical floodplain water-replenishment system. Riverbanks exposed by reduced discharge are marked in red. Insets show: (a) the Öregrét and Benda overflow weirs; (b) the Öregrét overflow weir; (c) the Vörösfűzes and Paducos branch area; and (d) the Denkpál branch-end closure		Photos: József Kertész.
54	Examples of complex hydraulic structures used to distribute and retain water within the active floodplain		Photos: József Kertész.
55	Öntési Lake (Öntési-tó) in the active floodplain		Photo: József Kertész.
56	The Mosoni-Danube during low flow in 1991		Photo: József Kertész.
57	Operation of the Mosoni-Danube water-supply system, shown with blue and yellow arrows (Dunai, 2024).		Source: Dunai (2024).
58	Lipót Oxbow Lake (Lipóti morotva) in the historical floodplain		Photo: József Kertész (2023).
59	The extent of the first phase of water replenishment completed by 1995		Map: Máté Chappon.
60	Denkpál fish passage		Photo: Gergely Ámon.
61	a) Locations of surface-water level gauging stations in Szigetköz. Gauging stations are monitoring points where river or channel water levels are measured regularly or continuously to track changes over time (Szűcs, 2009); b) Old Danube gauge at Doborgaz		Source: Szűcs (2018).
62	a) Cross-section locations for groundwater evaluation (b) Groundwater potential lines after water replenishment of the branches at cross section C (Chappon et al. (2024a)		Source: Chappon et al. (2024a).
63	(a-d) Modeling and calibration of the active floodplain branch system, showing typical flow velocities and water levels		Modeling and graphic: ÉDUVIZIG.

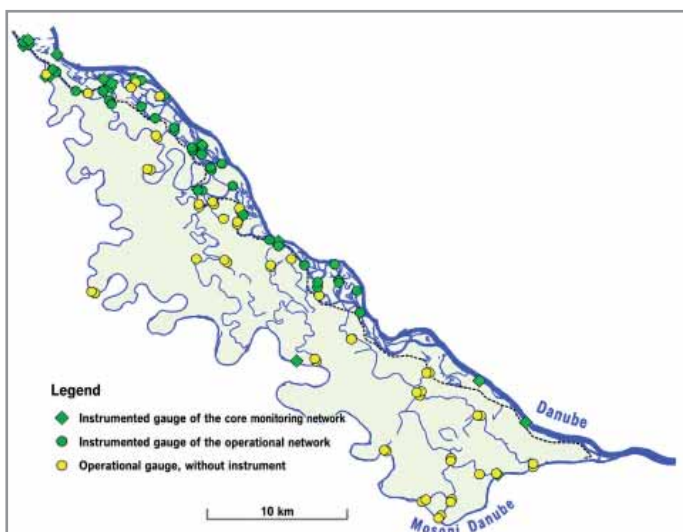
Fig. No.	Figure name	Link	Photo / figure credit
64	Daily water-level control at Dunakiliti		Photo: Máté Chappon; Graphic source: ÉDUVIZIG.
65	Flow in the toe-drain channel and its connection to the supply channel at the Rajka sluice gate		Photo: Klaudia Madarász.
66	Workflow for the development and approval of the operating permit		Graphic: Katalin Bene.
67	Function tree for the historical floodplain (Dunai, 1995)		Source: Dunai (1995).
68	Function tree for secondary objectives in the historical floodplain (Dunai, 1995)		Source: Dunai (1995).
69	Examples of multifunctional water management in the historical floodplain: (a) rehabilitation in Lower Szigetköz (Dunai, 2006); (b) double-functioning channel in the lower historical floodplain at Kisbajcs		Source: (a) Dunai (2006); Photo: (b) Máté Chappon.
70	Functions in space and time Janák et al. (2014)		Source: Janák et al. (2014).
71	Relationship between the Danube discharge measured at Bratislava (Dévény) and the flow entering the Hungari-an section at Rajka		Source: ÉDUVIZIG.
72	(a) Water-replenishment systems for the active floodplain; (b) the historical floodplain and the Mosoni-Danube		Graphic: Katalin Bene.
73	(a) Operating relationship between the Danube discharge at Bratislava (Dévény); (b) water supply to the Mosoni-Danube and the historical floodplain		Graphic: Katalin Bene.
74	Controlled floodplain inundation in the Szigetköz active floodplain.		Photo: József Kertész.
75	Process leading to the establishment of the Szigetköz Operating Committee		Source: ÉDUVIZIG.
76	Mosonmagyaróvár Barrage		Photo: Gergely Ámon.
77	Rehabilitation of the Mosoni-Danube: (a) Historical floodplain branch connection into the Mososni Danube upstream from Győr (b) River landscape in Győr; (c) small boat downstream from Győr; and (d) oxbow rehabilitation (Dunai, 2024)		Photos: (a-c) Máté Chappon; (d) Source: Dunai (2024).
78	Mosonmagyaróvár Barrage (b, c) and its surroundings on the Mosoni-Danube, and the Lajta control structure and fish passage (d)(Bencze, 2017)	http://mosonmagyarovar.network.hu/kepek/a_lajta_folyo_es_a_mellekagai/lajta_a_felujitott_mosonmagyarovari_duzzasztomu_kornyezete_a_hallepcsovel_felulrol_fenykepezve	Map: Klaudia Madarász; Source: (Bencze, 2017); Photos: webpage.
79	Water levels in Győr before and after construction of the Mosoni-Danube Outflow Structure	before http://vilagszam.hu/cikkek/derekadig-er-csak-a-mosoni-dunai-ilyet-ebben-az-evszazadban-meg-nem-lattal.html/3854 after https://utazik.hu/gyor-legerdekesebb-latnivaloi-terkeppel/	Source: website.

Fig. No.	Figure name	Link	Photo / figure credit
80	(a, b, c) Mosoni-Danube outflow structure near Győr, (d) DALIA project group picture at outflow structure		Photos: (a) Szilárd Németh, (b) Máté Chappon, (c, d) Dalia archive.
81	Ásványráró fish passage		Photo: Máté Chappon, 2025.
82	Extension of water replenishment through the lower Ásványi, Bagaméri, and Patkányosi branch systems, with photographs of fish passages source of base map: ÉDUVIZIG.		Photos: Máté Chappon, Gergely Ámon; Base map: ÉDUVIZIG.
83	(a) Lower active and historical floodplain (Kertész (2017); (b,c) Béka-ér siphon in Ásványráró supplying water from the (a) active floodplain to the historical floodplain.		Source: (a) Kertész (2017); Photos: (b, c) Máté Chappon
84	Rehabilitation of the multipurpose water-management network in the historical floodplain of Lower Szigetköz (Kertész, 2017)		Source: Kertész (2017).
85	Fish passages in lower Szigetköz; a) Zsejkei, b) Szavai, c) Zámolyi, d) Dunaszegi (Dunai, 2024)		Source: Dunai (2024).
86	Denkpál fish passage connecting the floodplain river branches and the Old Danube		Photo: József Kertész.

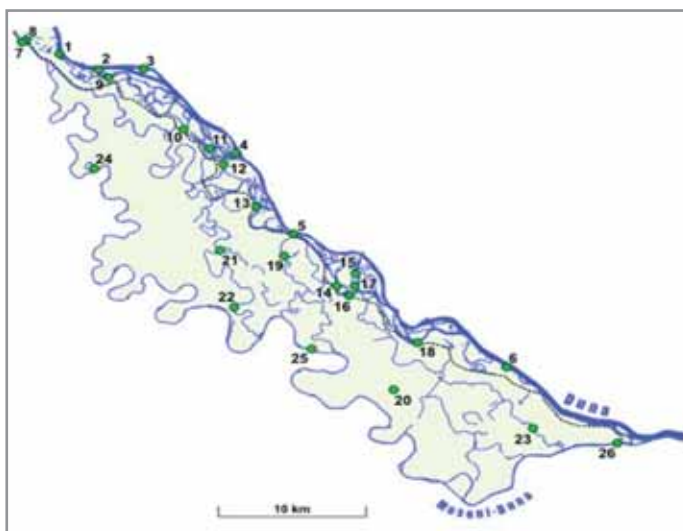
Appendix 1. Szigetköz monitoring – Components and Parameters

- Surface-water quantity
- Surface-water quality
- Groundwater levels
- Groundwater quality
- Soil moisture
- Forestry
- Biological monitoring
 - Botanical monitoring
 - Coenological surveys in 25 × 25 m plots
 - Leaf-area measurements
 - Weed-vegetation monitoring
 - Algae and moss monitoring
 - Phytobenthos
 - Algal communities
 - Mosses
 - Hydrobiological monitoring
 - Phytoplankton
 - Zooplankton
 - Macrophytes
 - Littoral macroinvertebrates
 - Fish
 - Zoological monitoring
 - Mollusks
 - Dragonflies
 - Bacteriological monitoring

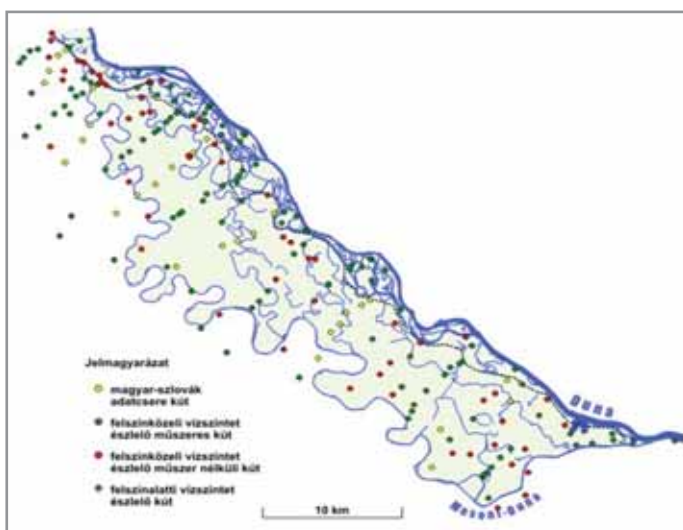
Monitoring locations



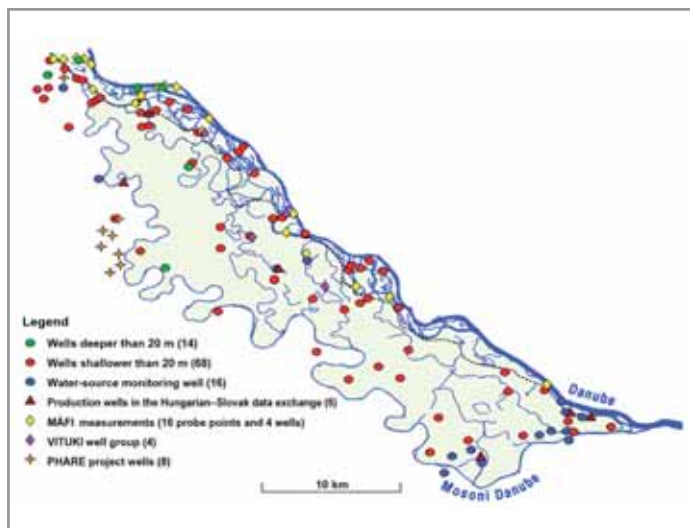
Water gauges



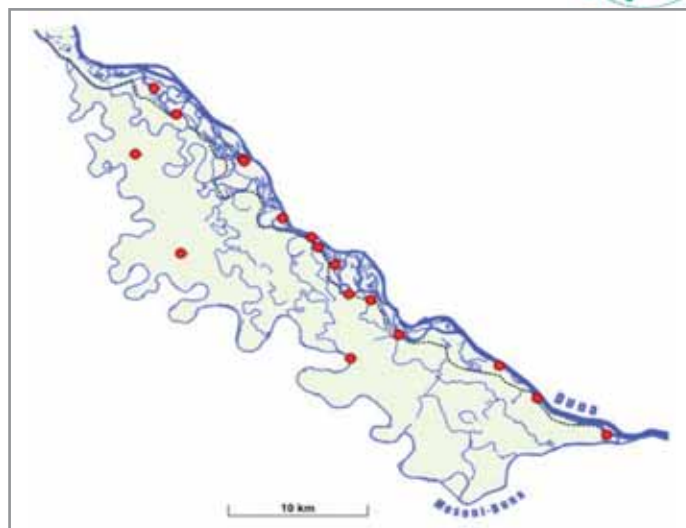
Water quality measurements



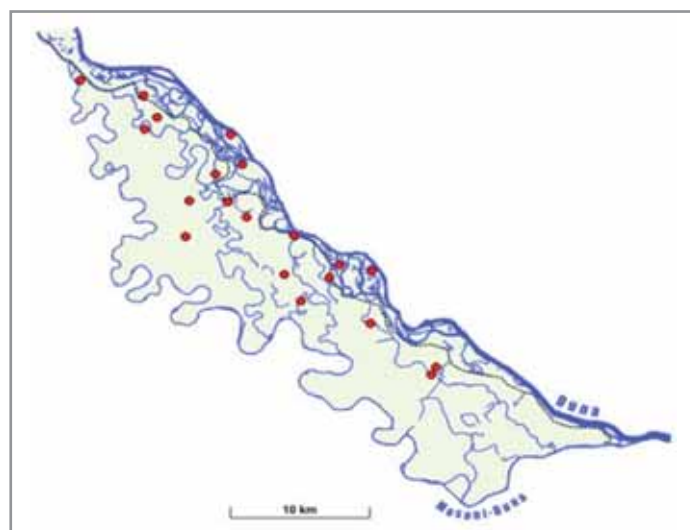
Wells



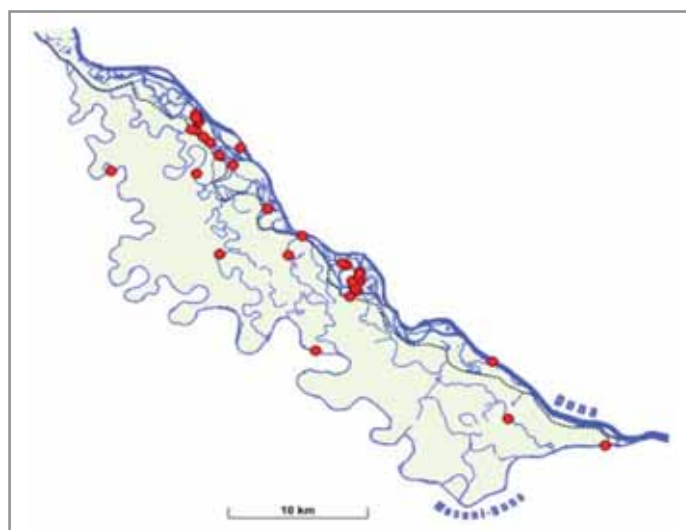
Groundwater quality monitoring sites



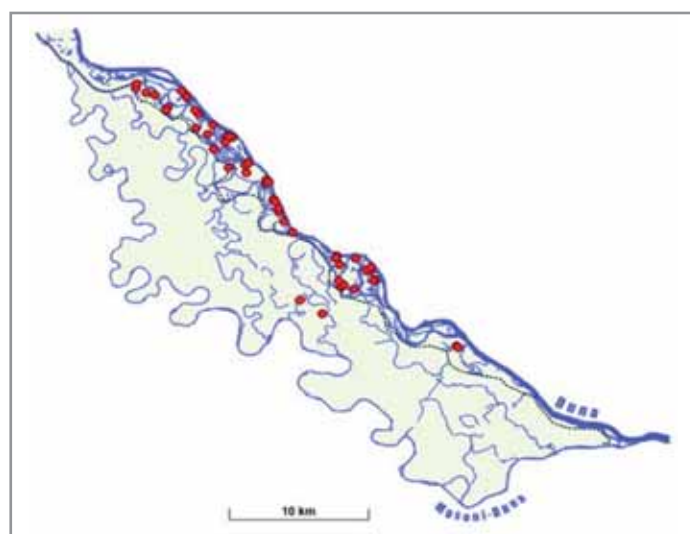
Botanical measurement locations



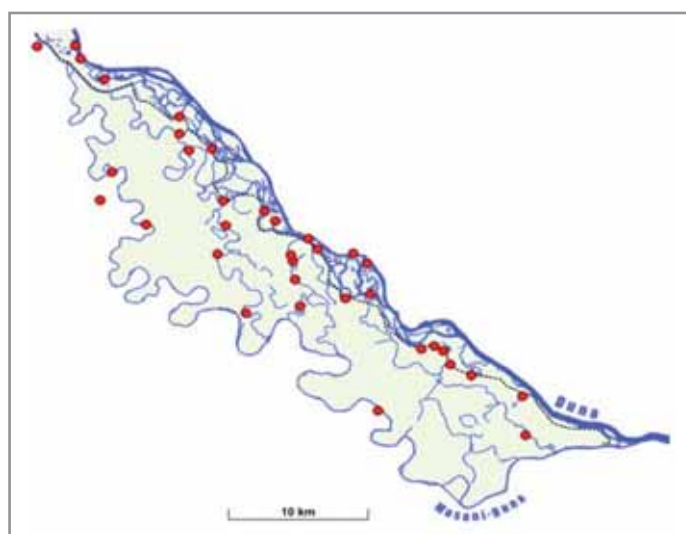
Moisture content measurement locations



Hydro botanical measurement locations



Forest monitoring locations



Zoological measurement locations

Blue —positive relationship White —neutral relationship
Red —negative relationship Green —both positive and negative relationships

Appendix 3. Operational Rules

Under general operating conditions, the extent of water replenishment is determined according to two discharge ranges measured at Bratislava (Dévény): normal operation and flood operation (ÉDUVIZIG, 2000).

I. Normal Operation

$$Q_{\min} < Q_{\text{Bratislava (Dévény)}} < \sim 4,650 \text{ m}^3/\text{s}$$

- Water distribution is determined based on discharge at Bratislava (Dévény).
- Water intake at Rajka ranges from 250 to 600 m³/s.
- Operators must ensure toe-drain channel-floodplain connectivity while preventing flooding on the protected side.

II. Flood Operation

$$Q_{\text{Bratislava (Dévény)}} > \sim 4,650 \text{ m}^3/\text{s}$$

- Water exceeding the capacity of the Gabčíkovo Hydropower Plant is released into the main channel of the Danube.
- A minimum discharge of 150 m³/s must be directed into the floodplain.
- Operation must avoid damage to floodplain infrastructure and the submerged weir.
- Rising water levels may cause inundation of the floodplain.
- The Dunakiliti barrage is fully opened.
- Seepage water on the historical floodplain side of levees increases, requiring strict monitoring of sluice gates 1 and 2.

III. Emergency Operation

Planned emergency operation is considered during:

- controlled floodplain inundation
- renovation of the system
- system flow measurement to ensure a stable supply of water for one to two days

IV. Unforeseen emergency operation may be required in the following circumstances:

- exceptional water pollution, deterioration of water quality, or unusual Danube discharge conditions;
- prolonged severe weather or ice conditions;
- failure of a water-level-control structure or flood-protection levee;
- an event endangering life or property in the active floodplain;
- restrictions required because of an emergency in the historical floodplain or the Mosoni-Danube;
- a sudden reduction in the discharge available for water replenishment.

The North-Transdanubian Water Directorate follows a pre-defined response plan and maintains continuous communication with the relevant authorities during emergencies. In a disaster situation, the operational center immediately informs the central flood-protection management body and requests intervention where necessary. A summary of the principal hydraulic structures of the replenishment system is provided in Appendix 4.

Appendix 4. Hydraulic Structures Governing Water Supply

Principal hydraulic structures

(ÉDUVIZIG, 2000b)

Submerged Weir at Danube River Kilometer 1843.0

The submerged weir at Danube rkm 1843.0 enables gravity-fed water replenishment of the Szigetköz active-floodplain branch system and, through that system, part of the protected-side branch network. The backwater created by the submerged weir allows water to enter the active floodplain through the modified Öregrét and Benda overflow weirs on the right bank of the Danube (rkm 1845,4 and 1845,9).

The discharge entering the floodplain depends on the water level upstream of the submerged weir. The remaining discharge continues along the Old Danube through the Dunakiliti Barrage and over the submerged weir.

Main dimensions:

- Location: Danube rkm 1843.0
- Total structure length: 320 m
- Crest width: 5.0 m
- Weir length: 200.0 m
- Average crest elevation: 122.25 mBf (meters above the Baltic elevation datum)
- Upstream slope: 1:3
- Downstream slope: 1:15
- Slope at the crest and bank connections: approximately 1:15

A gravel prefill was placed on the upstream side, and geotextiles were installed at the connections with the riverbanks.

Dunakiliti Barrage

The Dunakiliti Barrage, constructed at Danube rkm 1842.0, initially served only flood-conveyance functions until the submerged weir was completed. Under the 1995 Agreement, the discharge released into the Old Danube varies according to the hydrological conditions of the Danube. The discharge supplied to the active floodplain is also determined from the Danube discharge measured at Bratislava (Dévény).

Even during normal operation, the discharge passing over the submerged weir must be regulated. Limited operation of the Dunakiliti Barrage is used for this purpose. Unlike its originally intended function, the barrage does not create additional impoundment during this operation.

Instead, its gates and navigation lock are used to lower the upstream water level and maintain the required level in the main channel.

To protect the downstream riverbed and the foundation of the navigation lock, discharges greater than approximately 80–100 m³/s should not normally be released through the lock. Higher discharges require more frequent inspections and may result in costly maintenance. The operating organization determines the distribution of water through the Dunakiliti facilities in accordance with the applicable operating regulations. The technological equipment must be operated and maintained according to the relevant requirements.

Structures on the Hungarian Toe-Drain Channel and Connecting Channel

Rajka Water-Intake Sluice

Location: Chainage 60+784 of the flood-protection embankment

Function: Allows the required discharge to enter the Mosoni-Danube system while preventing floodwater from entering the drainage-channel network.

Dimensions: Twin sluice, each opening 3.75 × 3.75 m

Design discharge: 47 m³/s

Homokpart Sluice

Location: Chainage 8+759 of the toe-drain channel

Function: Conveys water from the Slovak toe-drain channel while maintaining a stable upstream water level.

Dimensions: Twin sluice, each opening 3.30 m wide

Design discharge: 25 m³/s

Záperdei Sluice

Location: Chainage 5+638 of the toe-drain channel

Function: Directs incoming water toward the Mosoni-Danube, the Gáncsomi oxbow lake, or the downstream sections of the drainage channel.

Dimensions: Twin sluice, each opening 3.30 m wide

Design discharge: 30 m³/s

Díósi Sluice

Location: Chainage 3+388 of the toe-drain channel

Function: Regulates the water level in the drainage channel and allows incoming water to pass downstream.

Dimensions: Twin sluice, each opening 3.30 m wide

Design discharge: 30 m³/s

Csőlősző Sluice

Location: Chainage 0+750 of the toe-drain channel

Function: Maintains the prescribed water level, conveys incoming water, and closes the drainage channel against floodplain water when necessary.

Dimensions: Twin sluice, each opening 3.30 × 4.70 m

Design discharge: 50 m³/s

Vigh Sluice

Location: Mosoni-Danube

Function: Supplies and regulates water entering the Mosoni-Danube and supports water supply to the Gáncsomi oxbow lake by controlling the water level in the drainage channel.

Dimensions: Twin sluice, each opening 6.00×3.00 m

Design discharge: $50 \text{ m}^3/\text{s}$

Structures of the Active-Floodplain Water-Replenishment System

Water replenishment requires the construction, operation, and maintenance of several types of hydraulic structures. In the previously planned and partly implemented active-floodplain system, water levels in the main branches were regulated by stone weirs that established the required levels within the adjoining channel compartments.

The target levels were determined using normal-discharge conditions assessed with an electrical analog model, together with boundary conditions related to forestry and nature-conservation requirements, local water withdrawals, and seepage characteristics.

The system was originally designed so that side branches received only enough flushing water to compensate for seepage losses. No additional flow was introduced through other branch closures. Access across the principal branches was provided mainly by ferries, except where permanent bridges or lock crossings were available. Under the later reduced-discharge conditions, several weirs had to be modified to allow water to pass through the system. The main design objectives were to:

- reproduce more natural water-level dynamics;
- provide adequate flow and water exchange;
- maintain the required water levels;
- preserve access for floodplain management;
- allow fish movement between selected channel compartments.

Because the implementation period was limited, much of the detailed design was undertaken concurrently with construction. Close cooperation between designers and construction engineers was therefore necessary.

Four principal types of hydraulic structures were used.

1. Low-Threshold Culverts

Low-threshold culverts were incorporated into branch closures to convey water through a closed cross-section, generally under pressurized-flow conditions. TUBOSIDER pipes were used in several locations. Their tendency to become obstructed by fine sediment limited their wider application.

2. Stone Weirs

Stone weirs were retained or constructed at locations where vehicle or management access across the channel was not required. Their principal advantage is that their dimensions and crest levels can be modified relatively easily.

3. Combined Control and Crossing Structures

These multifunctional structures provide water-level regulation, water conveyance, and access across the channel. They combine a high-threshold culvert, formed by narrowing the cross-section with removable beams, with a lower conveyance opening incorporated into a bridge structure.

Because local conditions included sediment-covered stonework, fallen trees, and financial constraints, deep foundations could not always be constructed. Existing masonry was therefore reinforced with integrated concrete elements and stabilized with geotextile layers. The high and low thresholds were placed as low as technically feasible. Typical dimensions were determined using SBG-66 bridge beams, with opening sizes varying according to beam length.

4. Adjustable Pipe-Sluice Structures

These structures use a TUBOSIDER pipe approximately 1.0 m in diameter. When open, the pipe functions as a culvert. When closed, adjustable sealing plates maintain the prescribed upstream water level while allowing controlled overflow, causing the structure to operate as a sharp-crested weir. The crest may be positioned approximately 2–3 m above the pipe threshold.

Branch-End Closures and Associated Structures

Branch-end closures prevent water introduced into the active-floodplain branch system from flowing back into the Old Danube. These structures are essential for retaining water and maintaining the required water levels within the branch network.

Water-intake structures connected to adjoining systems also contribute to replenishment. However, the discharges supplied through the gravity sluice at the Kisbodak I pumping station and the Dunaremete intake are small in relation to the total active-floodplain replenishment flow. The discharge used by the Denkpál sluice and fish passage depends on the water levels maintained in the Cikola branch system.

